URANIUM AND THORIUM IN ROCKS OF SOUTHWESTERN NEW BRUNSWICK

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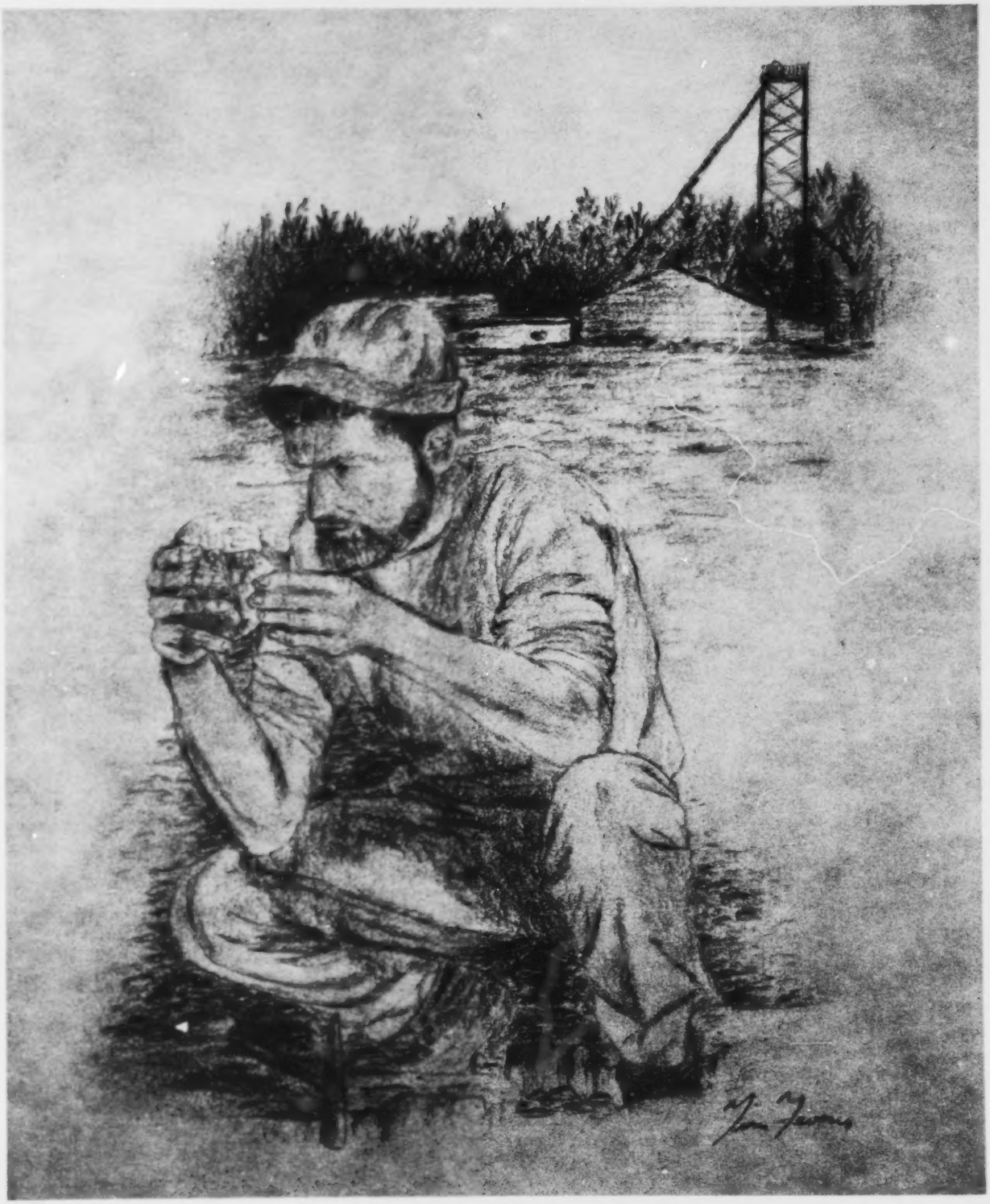

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Hon. Malcolm N. MacLeod, Minister

1987

URANIUM AND THORIUM
IN
ROCKS OF SOUTHWESTERN
NEW BRUNSWICK

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Map Plate 86-213 Generalized geological map of southwestern New Brunswick ..... in pocket

ABSTRACT

In situ gamma-ray spectrometry, carried out over an area of 17 000 km^2 in southwestern New Brunswick, suggests that the post-Acadian rocks have generally higher uranium and thorium contents than the pre-Acadian rocks; the Devonian granitic rocks of the Charlotte Pluton and the Mississippian rhyolitic rocks at Harvey Station have higher uranium and thorium contents than all other rocks in the area. This abundance in the younger rocks is due to depletion of uranium and thorium from the older rocks and reconcentration as a result of weathering, structural deformation and metamorphism. The older and less differentiated igneous rocks are believed to have been derived from magma originally containing low uranium and thorium.

Mafic to felsic rocks of the St. George Batholith display a curvilinear nine-fold increase in uranium and thorium with increase in the SiO_2 content; their Th/U ratio ranges from 1.8 to 9.0. The range is narrow for the rocks of the Bocabec Intrusive Complex, in the western end of the batholith, but wide for the rocks of the Charlotte Pluton, particularly in its eastern end. Although there are strong positive correlations of both uranium and thorium with SiO_2 and K_2O within the St. George Batholith as a whole, the correlations are poor in the Charlotte Pluton in eastern end of the batholith.

Magmatic differentiation is proposed as the essential control for uranium and thorium distribution in the St. George Batholith. Late hydrothermal and supergene processes operative particularly in the eastern part of this mass produced the uranium and thorium vein mineralization discovered along fractures.

The granitic rocks of the Charlotte Pluton, especially in its eastern end, are 'uraniferous' and are chemically, geologically and geophysically similar to other uraniferous granites in the U.S.A. and Europe. The abnormally low fluorine contents in the uraniferous granites of the Charlotte Pluton, relative to other uraniferous granites, is attributed to late-stage loss of fluorine with the volatile phase.

Radioelement mineralization in the Devonian granite of the Charlotte Pluton and Mississippian rhyolitic rocks at Harvey Station is of potential economic interest. Future exploration for radioactive elements in the area should be concentrated on the highly differentiated igneous rocks, particularly those of post-Acadian age that exhibit alteration associated with unconformity surfaces and shear zones.

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URANIUM AND THORIUM IN ROCKS OF SOUTHWESTERN NEW BRUNSWICK

INTRODUCTION

OBJECTIVES

The present study is designed to meet the following objectives: (1) to investigate the distribution of U and Th in rocks varying in age from Precambrian to Carboniferous in an area of about 17000 km^2 of southwestern New Brunswick, (2) to compare the distribution of U and Th in these rocks with global distributions for the same rock types, and to assess the rocks as possible hosts for economic uranium and throium deposits, (3) to examine the relationship between U and Th content and the petrogenetic development of the igneous rocks, (4) to determine the relationships among U, Th, major, minor and trace elements and compare geochemical characteristics of those rocks with relatively high U and Th concentrations.

PHYSIOGRAPHY AND GEOLOGICAL SETTING

The study area lies in the southwestern part of New Brunswick (Figure 1) and covers approximately 17,000 km^2. Fredericton is in the northeast corner of the area, which is bounded on the north and east by the Saint John River, on the south by the Bay of Fundy and on the west by the State of Maine, U.S.A.

The rocks in the study area range in age from Precambrian to Carboniferous (Plate 86-213). Triassic rocks were not included in this study. The area has a long and complex geological history that includes several periods of deformation and igneous intrusion. The maximum deformational effects occurred during the Acadian Orogeny in Early Devonian time. Most of the St. George Batholith, which includes the Bocabec Intrusive Complex, the Charlotte Pluton, the McDougall Lake Pluton and the Welsford Complex, was emplaced during mid-Devonian time (Pajari, 1976); the Eastern Charlotte Pluton is considered to have been emplaced during the Carboniferous (Ruitenberg and Fyffe, 1982).

The St. George Batholith is elongated parallel to the prominent northeast-southwest trend of the regional structure resulting from the Acadian Orogeny (Pajari, 1976). The western end of the batholith consists of gabbroic rocks intruded by adamellite (Fyffe, 1971). The batholith intruded Silurian and Devonian volcanic and sedimentary rocks on its southern margin. Precambrian and Ordovician rocks, including some older, deformed granitic types, have been intruded by the batholith along its southeastern margin. Along the northwestern and northeastern margins, the batholith has intruded Silurian greywackes,

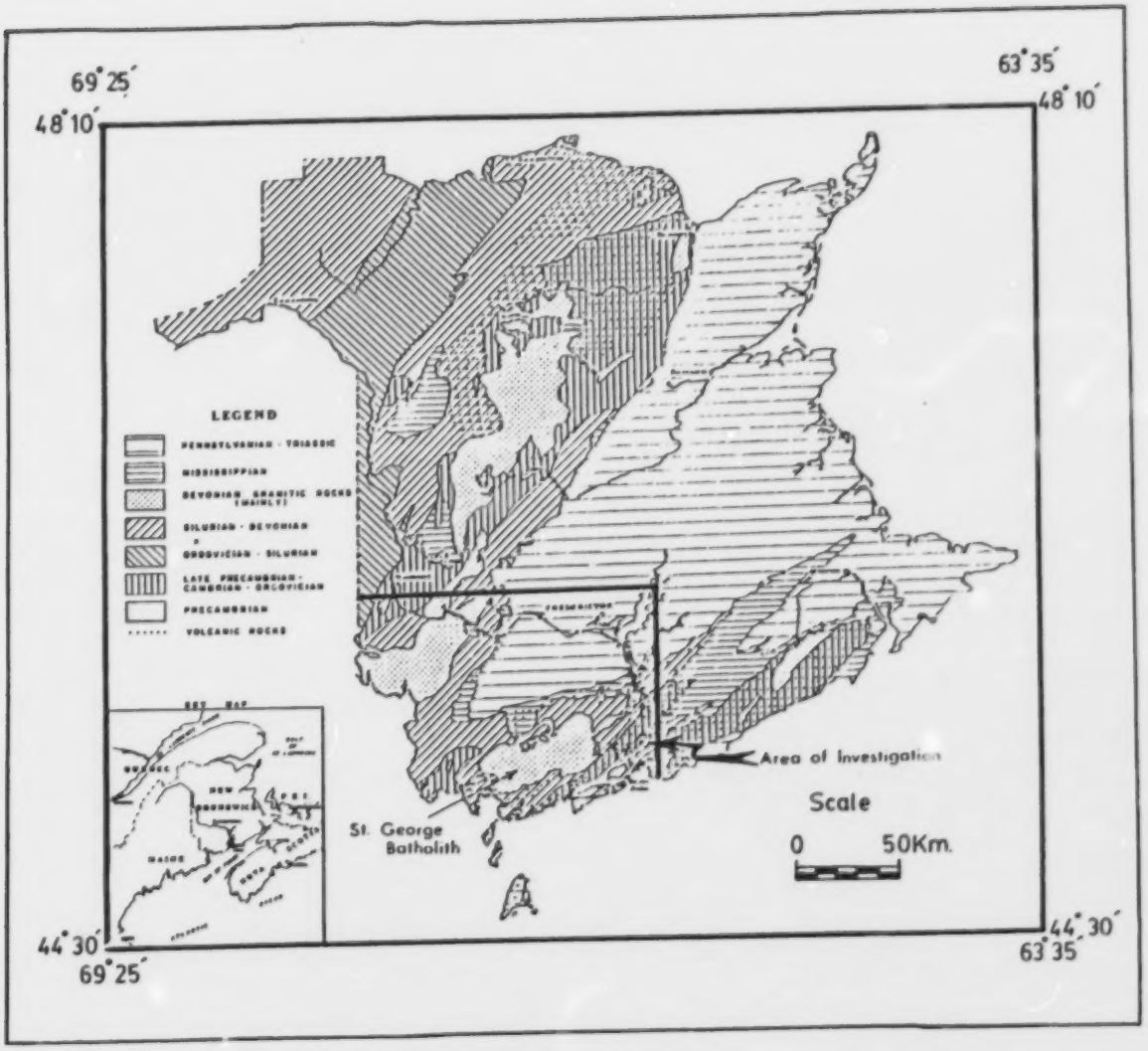


Figure 1. Location of the study area

siltstones, sandstones and slates. Mississippian volcanic rocks overlie both the granites and the older sedimentary rocks in the Mount Pleasant area to the north of the main body (Cherry, 1976).

Most of the rocks in the area have been affected to variable degrees by the Taconian, Acadian and Variscan orogenies. The Early Devonian Acadian Orogeny is the most important of these and affected most of the rocks in the area. The Taconian Orogeny in the Ordovician period disturbed some of the older rocks in the southwestern part of the area near St. Stephen (Pajari, 1976). The later Carboniferous Variscan Orogeny was limited to the coastal areas in the south (Rast and Grant, 1973) and did not affect the St. George Batholith or any of the granitic stocks in the area.

A generalized stratigraphy and correlation chart for the area, modified from Pajari (1976), is shown in Figure 2. The chart shows the events of volcanism and plutonism, and their relative and radiometric ages.

METHODS OF INVESTIGATION

A total of 3259 *in situ* gamma-ray spectometry assays of U, Th and K were carried out in southwestern New Brunswick during the autumn of 1979 and summers of 1980 and 1981 by using the 'GAD 6' gamma-ray spectrometer with a 7.5 x 7.5 cm NaI(Tl) detector. Details of the field procedure and gamma-ray spectrometer calibration, as well as lists of eU, eTh and K contents determined for various rock types and ages with their geographic locations, are given in Hassan (1984).

In addition, other investigators' samples from the Charlotte Pluton (Cherry, 1976), Bocabec Complex (Fyffe, 1971), South Oromocto Dyke, Milltown Granite, Eagle Lake Stock, Tower Hill Stock, Pleasant Ridge Stock, Musquash stock, Mohannas Stock (Butt, 1976) and the Mississippian volcanic rocks of the Mount Pleasant area (Gemmell, 1975) were analyzed for U and Th by INAA and DNAA, respectively. The rock samples were analyzed for SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5 and some minor and trace elements. The petrochemical analysis of these rock samples was accomplished by using X-ray fluorescence, atomic absorption spectrometry, flame emission spectrophotometry, and in some cases titrimetry in the Department of Geology, University of New Brunswick (Cherry, 1976; Fyffe, 1971; Butt, 1976; Gemmell, 1975).

Uranium and Th were also analysed by INAA and DNAA in two sets of granitic samples from drill core (Plate 86-213); one set was from the eastern end of the Charlotte Pluton (Trout Lake, drill location T2) and the other from its western end (Lily Lake, drill location L1).

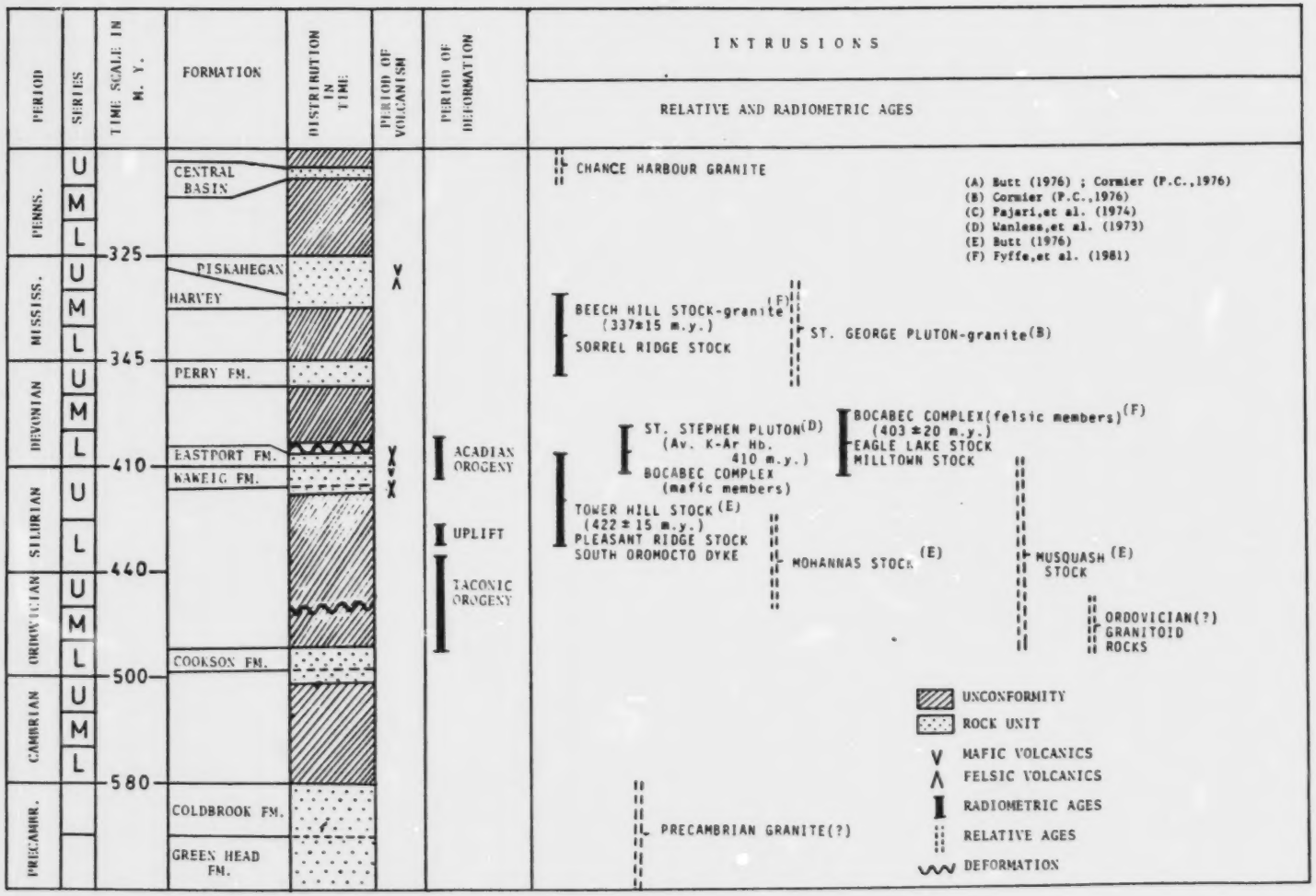


Figure 2. Generalized stratigraphy and correlation chart for southwestern New Brunswick.

Rock samples with high radioactivity were investigated by X-ray film autoradiography. The radioactive 'spots' indicated by the autoradiographs were identified by X-ray diffraction. Since most of the radioactive minerals are metamict, it is impossible to identify them by X-ray diffraction unless their crystallinity is restored. One way to restore their crystal structure is to heat them (Lima de Faria, 1964). The heat treatment generally used, and which was adopted in this work, is to heat the sample to 1000°C for one hour in an oven.

Usually secondary uranium minerals are not metamict (Steacy and Kaiman, 1978), or only partially metamict. Therefore, the crystals were X-rayed prior to heat treatment and run again after treatment. Unheated and heated single crystals were loaded in an X-ray camera with a Gandalfi attachment and run on a Philips X-ray machine using Cu-radiation (λ = 1.54178A, 40 Kv, 30 M$\propto$) and Co-radiation (λ=1.79021A, 40 Kv, 20 M$\propto$).

PREVIOUS INVESTIGATIONS

H.H. Huestis, a prospector, was the first to discover radioactive material in New Brunswick, at Harvey Station in 1954 (Gross, 1957). The uranium there (Plate 86-213) occurs in a band of rhyolite flows, rhyolite breccia, tuff, and agglomerate included in the Windsor Group of Mississippian age. Later, uranium was also discovered at the base of the Windsor Group in South Maitland, Nova Scotia (Charbonneau and Ford, 1978).

The discovery by Huestis led New Brunswick Uranium and Metals Limited to stake 180 claims over the Harvey Formation from York Mills to Harvey Station (Phillipson, 1972). Geiger counter surveys, rock sampling on radioactive zones and drilling of five holes at York Mills and Manners Sutton were carried out by this company during the period 1954 to 1958. This led to identification of three zones of radioelement concentration at York Mills, Manners Sutton and Harvey Station (Plate 86-213).

Most of the radioelement concentration in this area is associated with shear zones in the rhyolites and rhyolite tuffs. These shear zones are associated with the regional Fredericton Fault, which passes through York Mills and Harvey Station (Plate 86-213) and has a northeast-southwest strike. The highest uranium content is reported to be about 0.049% U_3O_8 at Manners Sutton. Fluorite accompanies the uranium concentration in this area. High radioactivity values have been found at many places in Harvey Station where the rocks have been altered to clay minerals and where quartz, pyrite or hematite have been introduced (Gross, 1957). Uranospinite, a hydrous calcium and uranium arsenate, and saleeite, a hydrated magnesium uranium phosphate, were identified in these occurrences by the Geological Survey of Canada (Gross, 1957).

At Manners Sutton (Plate 86-213), a specimen of banded, fine-grained crystalline rhyolite, transected by a reticulate network of thin purple fluorite veinlets was investigated by Gabelman (1981). Sericite and montmorillonite are the main alteration products of feldspar in this specimen. Gabelman found that feldspar and its alteration products were barren of uranium. The white fluorite was also found to be barren. Uranium was recognized only in the purple fluorite. Furthermore, Gabelman has found that the amount of uranium is directly proportional to the intensity of the purple color of the fluorite.

In 1972 extensive work was carried out by B.P. Oil Limited at Cherry Hill. Stream sediment, soil and rock sampling, and radon emanometry of stream sediment, soil and water have been carried out. In addition, 293 m of drilling was also conducted, but the results were not encouraging.

In 1978, Noranda Exploration Company Limited explored the Mississippian sedimentary rocks covering the felsic volcanic rocks. In this survey, well water sampling, radon emanometry for soils, scintillometric prospecting, stream sediment geochemistry and about 610 m of drilling were carried out, but no uranium mineralization is reported to have been found.

In 1976, radioactive materials were observed in strongly altered sandstones and volcanogenic conglomerates of the Carboniferous Carrow Formation near West Mill Settlement (Ruitenberg et al., 1976). Fine grains of uraninite were found in the Mount Pleasant deposit of Brunswick Tin Mines (Parrish, 1977).

During 1976, airborne gamma-ray spectrometric traverses were flown over New Brunswick at a 5 km line spacing, except for the area underlain by the Carboniferous Basin. The results were released by the Geological Survey of Canada in the spring of 1977 (G.S.C. Geophysical Series, Map 35721G).

The airborne radiometric maps and profiles of uranium, thorium, potassium and their ratios, as well as the uranium distribution in lake and stream sediments and water, measured by the neutron activation method (Austria, 1977) indicate that the exposed area of the St. George Batholith has higher concentrations of radioelements than other granites and surrounding rocks in southwestern New Brunswick.

Ford (1982) investigated the airborne radiometric data of New Brunswick. He stated that the regional radioactive anomalies in New Brunswick are related to granitic and rhyolitic rocks, with the more intense radioactive anomalies associated with the more differentiated phase of the Devonian-Carboniferous granites. He determined the average U, Th and K contents from 17 in situ radiometric readings over biotite granite of the Charlotte Pluton to be 5.9 ppm, 31.2 ppm and 3.5%, respectively.

Chandra (1981) investigated the airborne gamma-ray radiometric anomalies in New Brunswick by using truck-mounted and hand-held 'Scintrex-GAD6' gamma-ray sensors. Following the same technique described by Charbonneau et al. (1976) for the Canadian Shield, Chandra has established relationships between measurements made with the hand-held sensor and the airborne gamma-ray spectrometer over several areas in New Brunswick. He demonstrated that about 3 to 4 ppm eU on the airborne maps is related to 5 to 7 ppm eU in drift-covered areas and to 13 to 18 ppm eU in the underlying bedrock. To determine the uranium potential in rocks of New Brunswick, Chandra (1981) plotted the uranium favourability indices from the airborne radiometric data using the formulas of Saunder (1978). These maps illustrate that the felsic igneous rocks appear to be the most favourable host for uranium in southwestern New Brunswick relative to the other rock types.

Currently, the authors of this study are working on a research project for the Geological Survey of Canada to ivestigate the metallogenesis of uranium and associated elements in New Brunswick.

Regional aeromagnetic and gravity surveys of the study area have been made by the Geological Survey of Canada (1965) and the New Beunswick Department of Natural Resources (1979), respectively. McGrath (1970) investigated the magnetic properties of rocks in southwestern New Brunswick. He suggested that the pattern of magnetic anomalies over the St. George Batholith is caused by different phases which reflect either multiple intrusion or partial metasomatism. This interpretation was rejected by Cherry (1976). Cherry suggests anatexis in the crust as a source of the magma. He based his opinion on a detailed field and laboratory study of the of the St. George Batholith granites.

A 1:250,000 gravity map, compiled from data provided by the Earth Physics Branch of Energy, Mines and Resources and the D.N.R. (Wallace et al., 1979), indicates negative anomalies over the St. George Batholith which are due to the density contrast between the country rocks and the less dense granite.

GAMMA-RAY SPECTROMETRY SURVEY

Mean contents of eU, eTh, K and eTh/eU ratio and the standard error around the mean for the various rock types in the area are summarized in Table 1. The approximate area (estimated from the geological map) underlain by the individual rock type is also recorded, as is the sampling density (the number of determinations per square kilometre of the interpreted area for individual rock types).

In those rock types where higher radioactivity was detected along fractures, joints and in highly altered rocks, (e.g. Mississippian lava flows and the ash-fall tuff rhyolites), the mean eU, eTh, K and eTh/eU values are given with and without the anomalous values (Table 1). The mean eU and eTh values and their ranges, as well as the mean eTh/eU ratio, in the various rock types are displayed in Figure 3. The mean values shown exclude the anomalous values.

Four peaks associated with wide ranges and high mean eU and eTh contents are indicated in Figure 3. These peaks are produced by secondary uranium mineralization along fractures, joints and within hydrothermally altered rocks.

In map units that contain more than one rock type, the weighted mean contents of eU, eTh, K and eTh/eU ratio were calculated by taking into account the estimated area of the individual rock types in that unit. For example, if a certain map unit contains different rock types (A_1, A_2 ... An), the weighted mean eU, eTh, K and eTh/eU ratio content of the map unit can be calculated as follows:

$$X_n = \frac{\sum (X_r A_r)}{\sum A_r}$$

where,

X_n - the weighted mean eU, eTh, K and eTh/eU ratio content in the map unit.

X_r - the mean eU, eTh, K and eTh/eU ratio content in a rock type.

A_r - the estimated areas of a rock type.

n - number of rock types in the map unit.

URANIUM AND THORIUM DISTRIBUTION

Precambrian

Both eU and eTh contents are generally low in Precambrian rocks in comparison with eU and eTh contents in the younger rocks of the area (Table 1). The high mean eTh/eU ratio of 9.87 ± 2.59 and low eU contents in the Precambrian metasedimentary rocks suggest that U has been depleted relative to Th.

The mean eTh/eU ratio in the Precambrian rhyolite is relatively higher than the global average of 3.3 for rhyolitic

Table 1
Mean Content of eU, eTh, K and eTh/eU Ratio
and Sampling Density of Rocks of Southwestern New Brunswick

AGE		ROCK TYPE	No. OF DETERMINATIONS	AREA OF INDIVIDUAL ROCK TYPE (sq. km.)	SAMPLING DENSITY (NO OF DETERMIN PER 50 KM.)	MEAN AND STANDARD ERROR AROUND MEAN			
						eU(ppm)	eTh(ppm)	K(%)	eTh/eU
PENN.		granite	50	6.0	8.3	2.21±0.08	17.30±0.46	4.08±0.07	8.65±0.54
		sandstone	150	994.5	0.1	1.97±0.07	9.47±0.02	1.86±0.07	5.43±0.20
		conglomerate	97	331.5	0.3	1.94±0.05	9.22±0.17	1.88±0.04	5.17±0.20
MISS./PENN.		siltstone	36	104.0	0.3	1.44±0.05	7.52±0.18	0.87±0.03	5.52±0.28
		conglomerate	11	69.2	0.2	2.39±0.34	16.32±3.62	1.95±0.06	6.56±0.82
MISSISSIPPIAN		paleosoil	12	0.1		27.72±4.51	49.04±3.85	3.59±0.28	2.49±0.51
		lava flows rhyolite	110	13.3	8.3	25.18±8.69 (3.84±0.17)	39.50±1.39 (36.59±0.83)	4.74±0.09 (4.74±0.08)	9.71±0.67 (11.39±0.68)
		ash fall tuff rhyolite	70	10.4	6.7	13.53±2.58 (4.09±0.51)	35.76±1.17 (33.17±1.18)	4.41±0.16 (4.40±0.18)	7.93±0.63 (9.86±0.59)
		ash flow tuff rhyolite	48	6.0	8.0	8.14±0.78	44.60±1.30	4.13±0.17	7.27±0.51
		shale	9	1.8	4.9	3.29±0.51	19.66±4.72	3.72±0.30	6.19±0.86
		siltstone	25	6.2	4.0	7.11±1.81	25.43±2.49	3.68±0.21	5.11±0.39
		sandstone	14	5.2	2.7	2.56±0.22	14.32±1.54	2.31±0.15	5.80±0.42
		conglomerate	14	4.4	3.2	4.92±0.16	44.24±1.23	2.18±0.10	9.09±0.31
DEVONIAN	PERRY FM.	conglomerate	43	14.8	2.9	3.26±0.10	14.63±0.27	2.95±0.05	4.67±0.18
	CHARLOTTE PLUTON	aplite	57	0.2		8.20±0.33	40.22±1.63	4.22±0.07	5.21±0.23
		microgranite	15	0.1		17.33±0.97	56.67±2.19	3.58±0.09	3.33±0.11
		porphyritic granite	290	160.4	1.8	7.81±0.16	35.88±0.47	4.13±0.03	5.00±0.10
		coarse-grained granite	409	641.4	0.6	7.01±0.36 (6.41±0.12)	40.16±2.40 (35.87±0.39)	4.17±0.03 (4.17±0.02)	6.08±0.09 (6.07±0.10)
	L.McDOUGAL PLUTON	megacrystic porphyritic granodiorite	52	238.4	0.2	4.05±0.24	20.81±0.48	3.17±0.07	5.82±0.29
	BOCABEC COMPLEX	West End granite	19	28.6	0.7	4.40±0.35	28.02±1.55	4.52±0.19	6.90±0.49
		alaskite	52	14.3	3.6	3.37±0.15	16.27±0.58	3.05±0.09	5.02±0.16
		granodiorite	34	7.3	4.7	2.96±0.17	16.93±0.64	2.52±0.12	5.71±0.48
		diorite	17	4.4	3.8	1.47±0.13	9.96±0.83	1.90±0.15	7.74±1.05
		gabbro	108	88.7	1.2	0.78±0.53	4.02±0.22	0.96±0.04	7.47±0.78
	EASTPORT FM.	diabase dyke	37	1.0	37.0	2.08±0.08	8.43±0.27	1.26±0.07	4.37±0.17
		rhyolitic tuff	94	29.6	3.2	4.30±0.15	22.75±0.47	3.61±0.15	5.61±0.21
		rhyolitic lava flow	73	19.8	3.7	5.15±0.18	26.78±0.83	4.58±0.11	5.47±0.17
		andesite	88	8.8	10.0	2.62±0.08	11.57±0.15	1.86±0.05	4.75±0.15
		basalt	86	9.9	8.7	1.22±0.06	5.15±0.28	0.99±0.06	4.68±0.27
		shale	43	7.8	5.5	3.43±0.13	14.93±0.51	2.89±0.11	4.53±0.16
		siltstone	70	12.0	5.9	3.44±0.10	13.73±0.30	2.68±0.09	4.13±0.10
		sandstone	22	4.9	4.5	3.35±0.14	13.78±0.52	2.41±0.12	4.19±0.15
		conglomerate	22	4.9	4.5	2.73±0.15	12.13±0.64	1.56±0.11	4.59±0.24
SIL./DEV.		granite	12	20.0	0.6	2.25±0.14	13.73±0.70	3.33±0.11	6.43±0.50
		rhyolite	18	15.3	1.2	6.98±1.76 (4.05±0.30)	28.62±4.85 (21.66±0.89)	3.65±0.19 (3.67±0.22)	4.85±0.41 (5.00±0.43)
		metasedimentary rocks	5	15.3	0.3	4.94±0.65	21.86±0.53	3.48±0.24	4.74±0.63
SILURIAN		lamprophyre dyke	15	0.1		6.74±0.45	33.34±1.88	3.69±0.15	5.09±0.27
		shale	193	133.9	1.4	4.04±0.16	15.96±0.16	4.12±0.05	4.43±0.10
		sandstone	298	486.5	0.6	3.32±0.08	13.98±0.15	2.75±0.04	4.57±0.08
		conglomerate	28	19.0	1.5	3.12±0.13	12.48±0.48	2.58±0.14	4.12±0.20
ORDOV.		granite	156	21.6	7.2	2.17±0.08	17.91±0.46	3.90±0.08	9.90±0.49
		granodiorite	31	14.3	2.2	1.04±0.06	5.39±0.34	1.54±0.05	6.05±0.92
		metasedimentary rocks	50	109.2	0.5	3.03±0.09	14.51±0.49	2.93±0.11	4.90±0.16
PRECAMB.		granite	103	23.9	4.3	1.83±0.05	9.59±0.15	2.37±0.03	5.66±0.18
		gabbro	19	14.3	1.3	0.31±0.06	1.76±0.30	0.33±0.05	5.67±1.23
		rhyolite	23	35.9	0.6	2.39±0.19	14.31±0.93	2.09±0.22	6.27±0.36
		metasedimentary rocks	31	45.8	0.7	0.99±0.11	6.05±0.67	1.15±0.08	9.87±2.59

Values with mineralized zones excluded are given in brackets ().

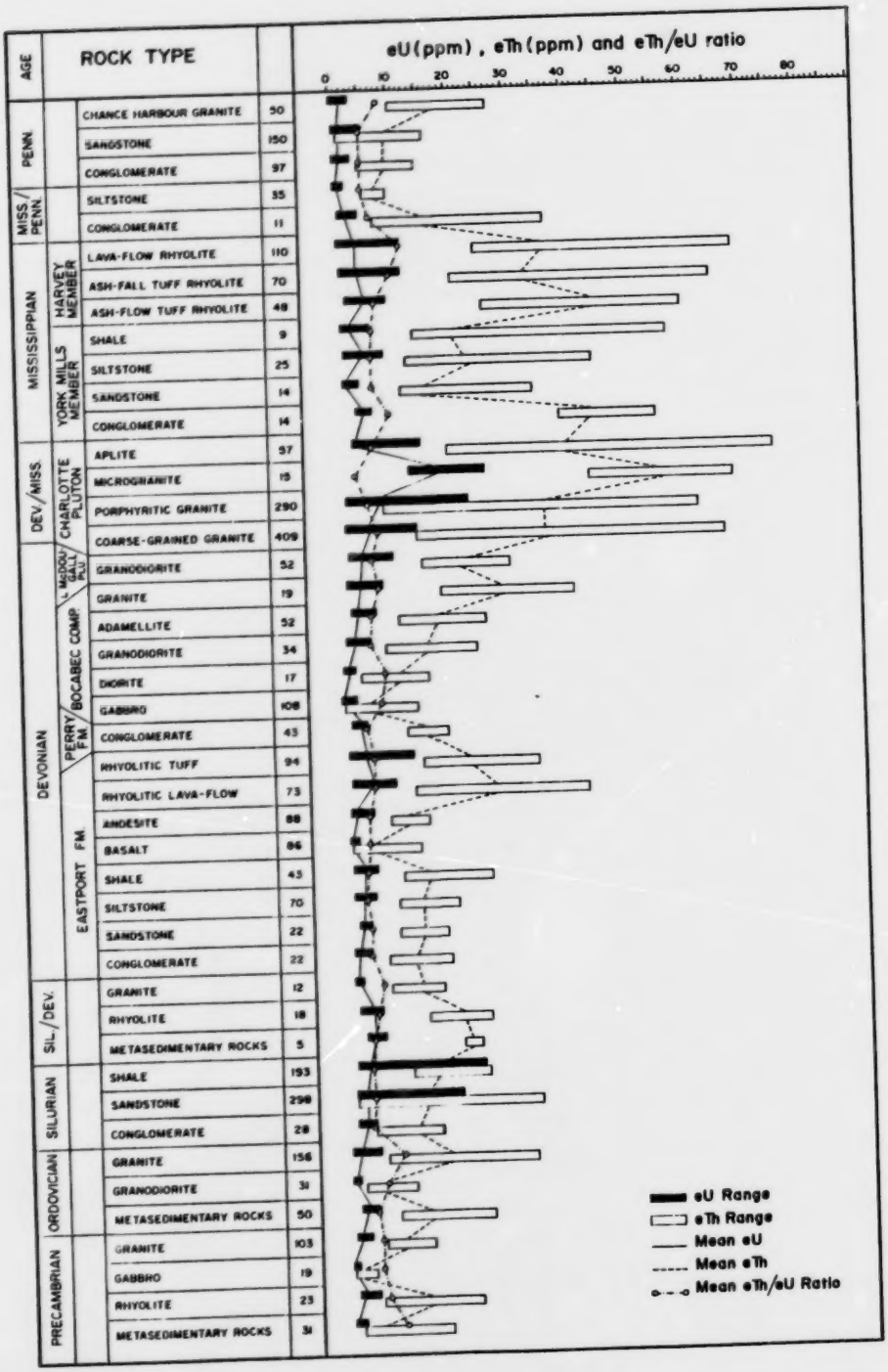


Figure 3. Mean eU, eTh and eTh/eU ratio in rocks of southwestern New Brunswick.

rocks given by Boyle (1982). This could be explained by leaching of U relative to Th in the rhyolite, presumably by post-crystallization processes such as weathering. Alternatively, the Precambrian rhyolite could be derived from magma containing initially low U and Th with Th being proportionally more abundant than U relative to the global average.

Equivalent U, eTh and K contents are higher in the Precambrian felsic rocks than the mafic rocks of the same age. This pattern of eU and eTh increase within more felsic rocks is a common phenomenon in rocks of all ages. The eTh/eU ratio, however, remains fairly constant in the felsic and the mafic rocks.

Both eU and eTh content of the Precambrian granites are much lower than those of 'global' average granitic rocks, which are 4.5 ppm eU and 15.0 ppm eTh (Boyle, 1982). This suggests that either U and Th were depleted from these rocks, presumably by successive orogenic activities or by metamorphic processes accompanying these orogenies. Orogenic movement can produce shear zones which serve as channelways for waters circulating through these rocks and hence uranium could have been leached. Alternatively, the Precambrian granites could be derived from a source containing lower U and Th than Phanerozoic granites. The first explanation is plausible since these rocks are highly deformed, metamorphosed and to some extent altered; the second is difficult to evaluate.

Ordovician

It appears that eU, eTh and K increase in the Ordovician metasedimentary rocks relative to the Precambrian metasedimentary rocks. The eTh/eU ratio, however, is lower in these rocks than their Precambrian counterparts.

The eU, eTh, and K contents, as well as the eTh/eU ratio, appear to increase with the degree of magmatic differentiation of the Ordovician intrusive rocks. In comparison with 'global' averages of U (4.5 ppm in granites and 2.0-4.5 ppm in granodiorites according to Boyle, 1982) the U is relatively lower in the Ordovician intrusive rocks of southwestern New Brunswick. This may suggest that these Ordovician intrusive rocks were derived from a source magma with low U content. The high eTh/eU ratio in the Ordovician intrusive rocks relative to their global averages may indicate that U was depleted relative to Th in these rocks, probably by weathering, or that Th may be proportionally higher than U in the source rocks.

Silurian

The mean eU, eTh and K contents in the Silurian sedimentary rocks are higher in the fine-grained member of these rocks. This may be explained by more leaching of U from the coarser, highly porous conglomerates and sandstones, or due to

adsorption of U, Th and K by the clay minerals and organic materials abundant in shale. The latter explanation is preferable because, in addition to U (mobile), both Th and K contents (immobile) were also increased with the finer rocks. The eTh/eU ratio does not change significantly with the fining of these rocks thus supporting the adsorption hypothesis.

The weighted mean eU, eTh, K contents and the eTh/eU ratio in the Silurian metasedimentary rocks in the estimated area covered by conglomerate, sandstone and shale were calculated to be 3.46 ppm, 14.35 ppm, 3.03% and 4.53, respectively. The weighted mean eU, eTh, and K contents reveal that U contents in the Silurian sedimentary rocks are slightly higher than in the Ordovician metasedimentary rocks, whereas their Th and K contents are almost the same. The increase in U content in the Silurian sedimentary rocks relative to the Ordovician sedimentary rocks (without significant increase in Th and K), may reveal that these rocks were subjected to similar geological processes during past geological times. Because of the age differences between the Silurian and Ordovician sedimentary rocks, the amount of U leached, probably by weathering, is higher in the Ordovician rocks.

Relatively high eU and eTh contents were determined in the mafic biotite lamprophyre dyke intruding the Silurian metasedimentary rocks (Mactaquac Dam area). In comparison to global averages of 5.0 ppm U and 15.0 ppm (Boyle, 1982), the New Brunswick lamprophyre contains slightly higher U and twice as much Th. This suggests that either a substantial amount of U is depleted in these rocks or these rocks were initially derived from source magma containing relatively higher Th than U. Although the genetic relationship between these dykes and the intrusive bodies of the area is unknown, the eU and eTh contents are higher than those of the igneous rocks, with the exception of the Charlotte Pluton of the St. George Batholith.

Silurian/Devonian

The mean eU, eTh and K contents in the Silurian/Devonian rocks are higher than the mean eU, eTh and K contents in the older metasedimentary and igneous rocks. A small uranium deposit (Lepreau) is located northwest of Seven Mile Lake (Lat. 45° 14' 15"; Long. 66° 28' 50"). The higher eU and eTh contents are recorded along fractures where sulphide concentration took place (Figure 4). These mineralized fractures are located at the contact of these rocks with Charlotte Pluton granite. It appears that the uranium and thorium are genetically related to the sulphide mineralization in the chloritized rhyolite because the high eU and eTh contents are only associated with sulphide-bearing fractures (Figure 4). A surface autoradiograph of sample S448/458H taken from the mineralized zone indicates that U and Th occur along randomly oriented microfractures within this rock (Figure 5).

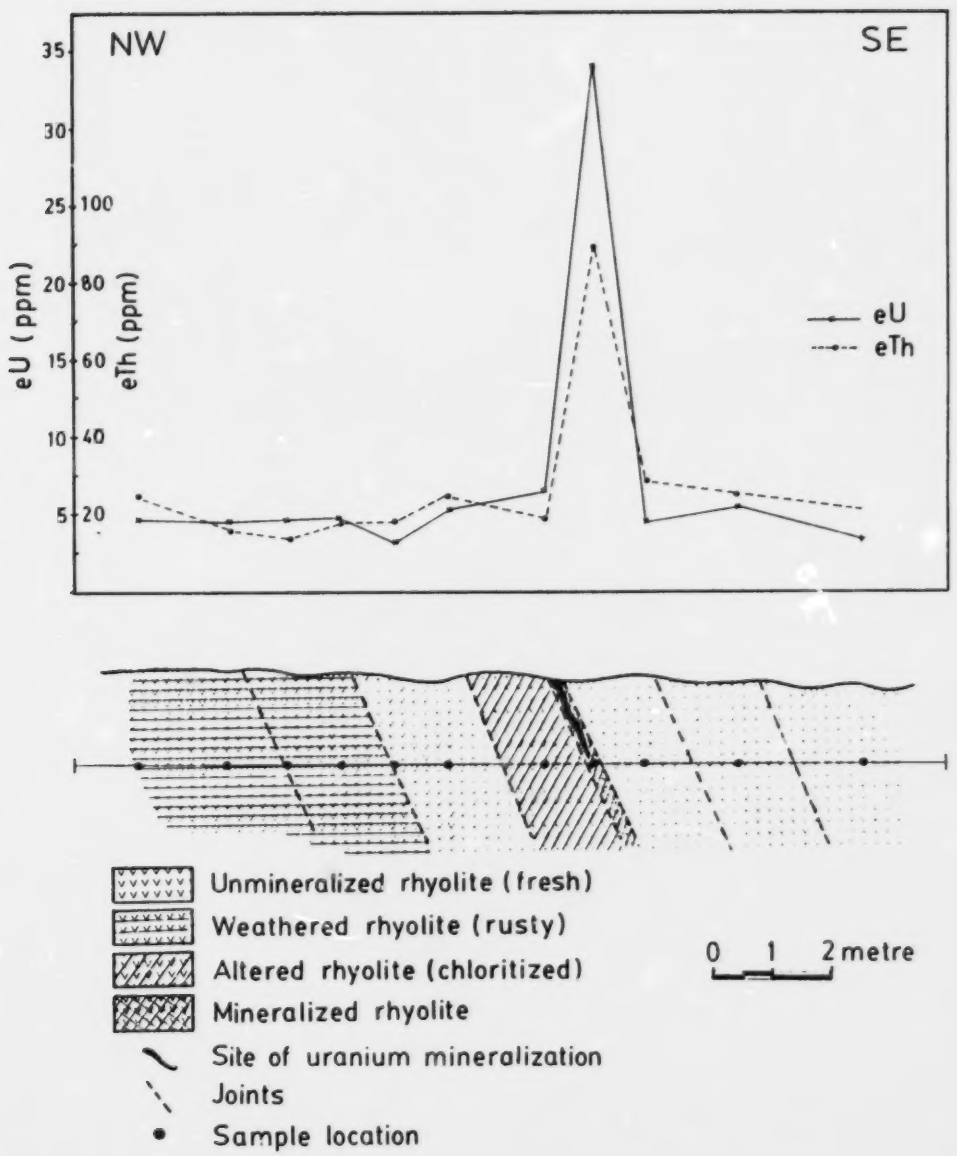


Figure 4. Sketch of the mineralized zone in the Silurian/ Devonian rhyolites (lat. 45° 14' 15"; long. 66° 28' 50").

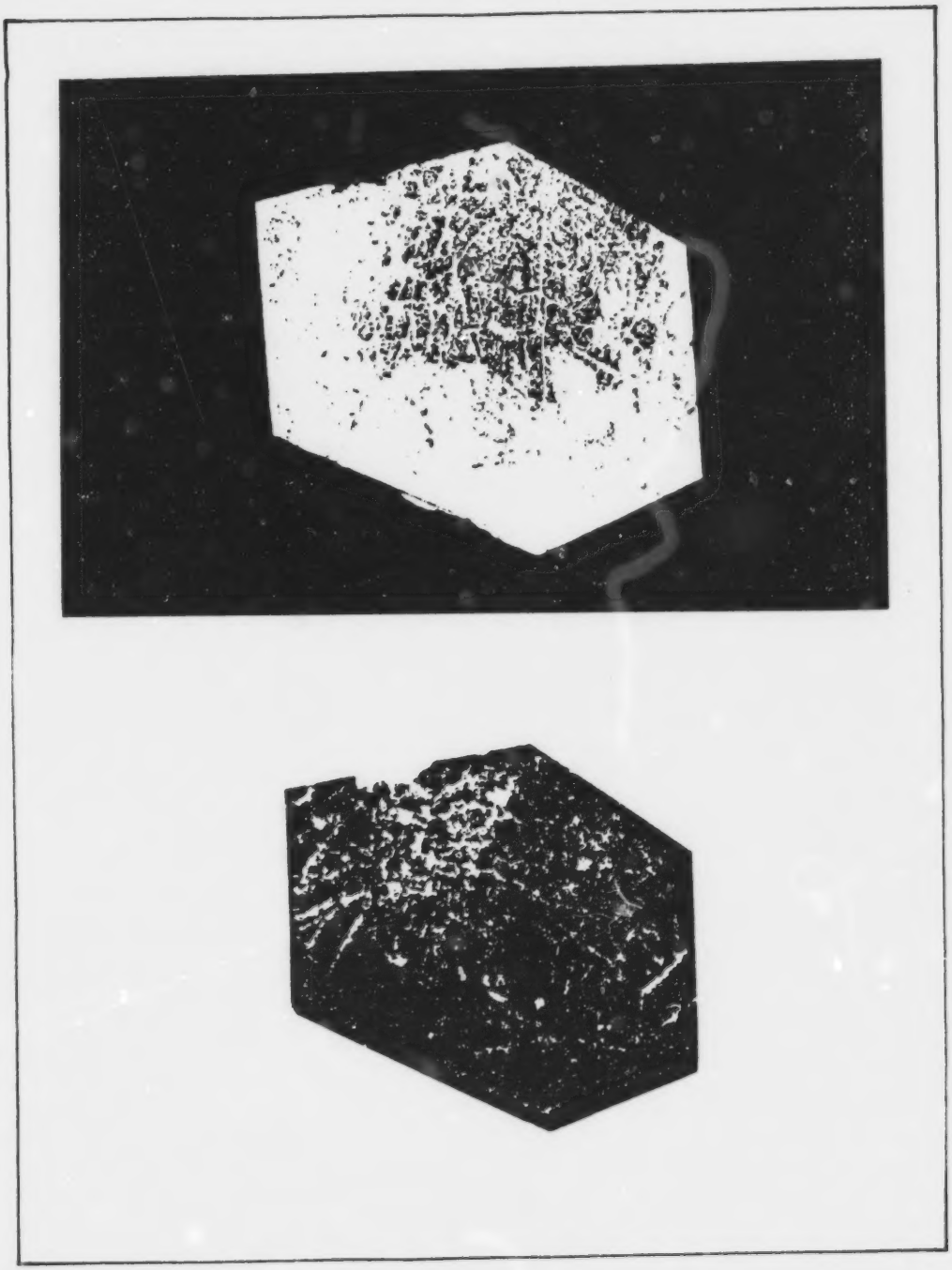


Figure 5. Above: Silurian/Devonian rhyolite (sample S148/458H; actual size). Below: Surface autoradiograph of rhyolite sample above. Radioactive spots appear bright.

The granitic rocks have lower eU, eTh and K than the volcanic rocks. Although eU is a little higher, both eTh and K are lower than in the Ordovician granite.

Devonian

Sedimentary Rocks: Similar to the Silurian metasedimentary rocks, and probably for the same reason, the mean eU, eTh and K contents in the sedimentary rocks of the Devonian Eastport Formation are higher for the finer rocks (Table 1). A marked increase in both eU and eTh contents occurs from the conglomerate to the sandstone, with a smaller increase observed in eU from sandstone through shale. However, eTh content remains constant in the sandstone and the siltstone, but an obvious increase of eTh is indicated in the shale.

The weighted mean eU, eTh and K contents and eTh/eU ratio calculated for the sedimentary rocks of the Eastport Formation are 3.30 ppm, 13.79 ppm, 2.50% and 4.32, respectively. These averages are slightly lower than those of the Silurian metasedimentary rocks, perhaps because these Devonian sedimentary rocks were deposited in a shallow-water, suboxidizing environment, whereas the Silurian sedimentary rocks were deposited in a deep-water, reducing environment (Pickerill et al., 1978).

The mean eU, eTh and K contents in the Upper Devonian Perry Formation conglomerate are higher than those of the Lower Devonian Eastport Formation conglomerate. The best explanation for this is that the source rocks (provenance) of the Perry Formation are mainly the Devonian intrusive rocks, which have higher U, Th and K contents than the older source rocks in the area.

Volcanic Rocks: The mean eU, eTh and K contents and eTh/eU ratio are higher in the younger, more felsic members of the volcanic rocks of the Devonian Eastport Formation than in the mafic rocks (Figure 6). The eU-eTh, eU-K and eTh-K variation diagrams for the Devonian volcanic rocks have been plotted in Figure 7. A strong geochemical coherence among eU, eTh and K during the magmatic evolution of the volcanic rocks can be observed from the high positive correlation coefficient calculated between each pair of these radioelements. The relationship between eU and eTh is very strong as indicated by the positive correlation coefficient of 0.85 (Figure 7). It appears from Figure 7 that for rocks with high eU and eTh contents (above 5 ppm eU and 18 ppm eTh) the relationship between eU and eTh is poorer than for rocks of low eU and eTh contents. The correlation coefficient between eU and eTh for rocks with high eU and eTh contents is 0.41, whereas for rocks with low eU and eTh, the correlation coefficient is 0.83. A possible explanation is

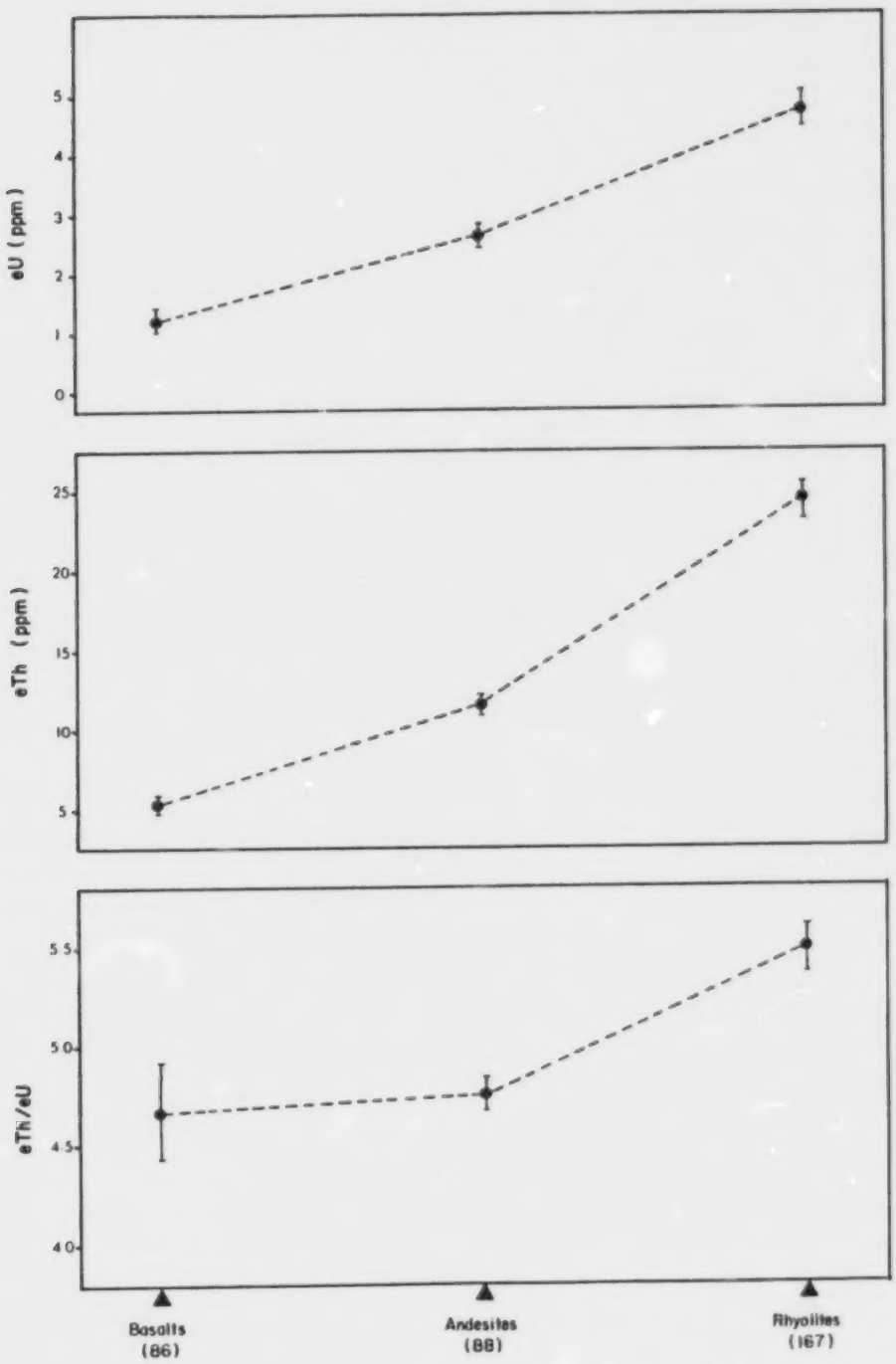


Figure 6. Mean eU, eTh and eTh/eU ratio distribution in the Devonian volcanic rocks of Eastport Formation.

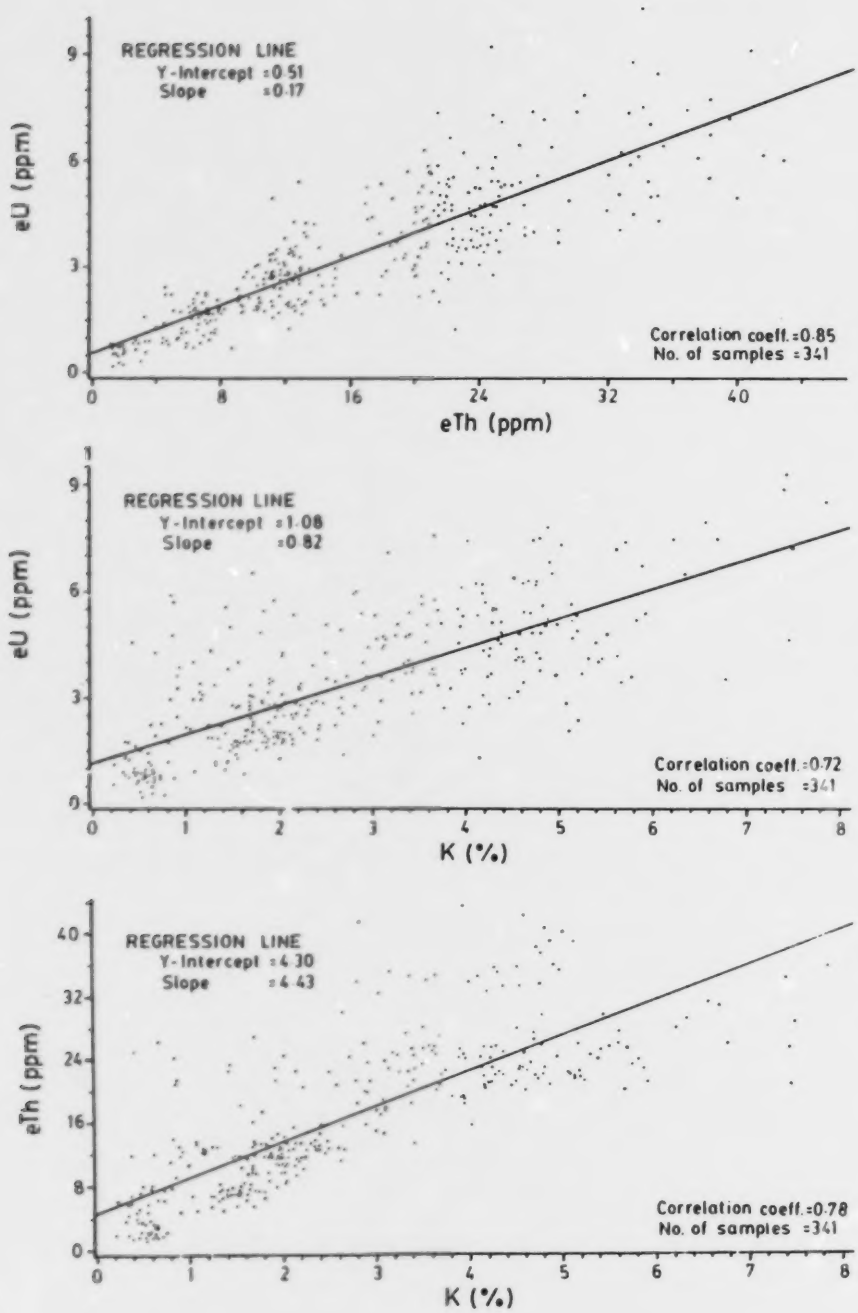


Figure 7. Plots of eU vs. eTh, eU vs. K, and eTh vs. K in the Devonian volcanic rocks of the Eastport Formation.

that either P_{O_2} increased during the crystallization of these rocks or a secondary geologic process such as alteration or weathering has prevailed. Alternatively, the effect of these two factors may have been combined.

The relationship between eTh and K in the volcanic rocks (Figure 7) is stronger than the relationship between eU and K. This suggests that U (relatively mobile) is depleted relative to Th and K (relatively immobile) in these rocks, presumably by postmagmatic processes such as weathering.

Intrusive Rocks: From the mean eU, eTh, K contents and eTh/eU ratio of individual Devonian rocks of the St. George Batholith, and from the estimated areas underlain by the various rock types, the weighted mean eU, eTh and K contents and the eTh/eU ratio of the St. George Batholith are calculated to be 5.58 ppm, 29.81 ppm, 3.70% and 5.99, respectively.

A comparison of the eU and eTh contents of the St. George Batholith's mafic to felsic members (Figure 8) indicates a trend of increasing eU and eTh with increasing felsic character of the rocks, except for the Bocabec Intrusive Complex adamellite which probably includes hybrid rocks of intermediate composition. The eTh/eU ratio appears to be erratic, suggesting a complex history of U leaching and redistribution in these rocks.

The eU-eTh, eU-K and eTh-K variation diagrams for the rocks of the St. George Batholith are displayed in Figure 9. A strong positive correlation (0.77) is indicated between eU and eTh (Figure 9). The linear regression model predicts five times as much eTh and eU in the batholith. This may reflect a normal or near normal crustal ratio of Th to U resulting from magmatic processes.

A uranium prospect has been discovered on the top of the Eagle Rock Cliff, near Welsford, along fractures in a poorly exposed outcrop of coarse-grained granite of the Charlotte Pluton (latitude 45° 25' 50" and longitude 66° 18' 56"). The eU and eTh contents of this zone are as high as 112 ppm and 766 ppm, respectively. The rocks have a deep red colour and are highly fractured and silicified. The autoradiographs of samples collected in this zone are shown in Figures 10 and 11. The minerals from the highly radioactive spots on these autoradiographs were identified by X-ray diffraction as uraninite and thorite.

Volcanic Rocks versus Intrusive Rocks: A comparison of the mean eU and eTh contents of the Devonian Eastport volcanic rocks and the rocks of the Devonian Bocabec Intrusive Complex is presented in Figure 12. In both the volcanic and intrusive rocks, eU and eTh are higher in the more felsic and apparently younger members. Comparable increases in both eU and eTh are

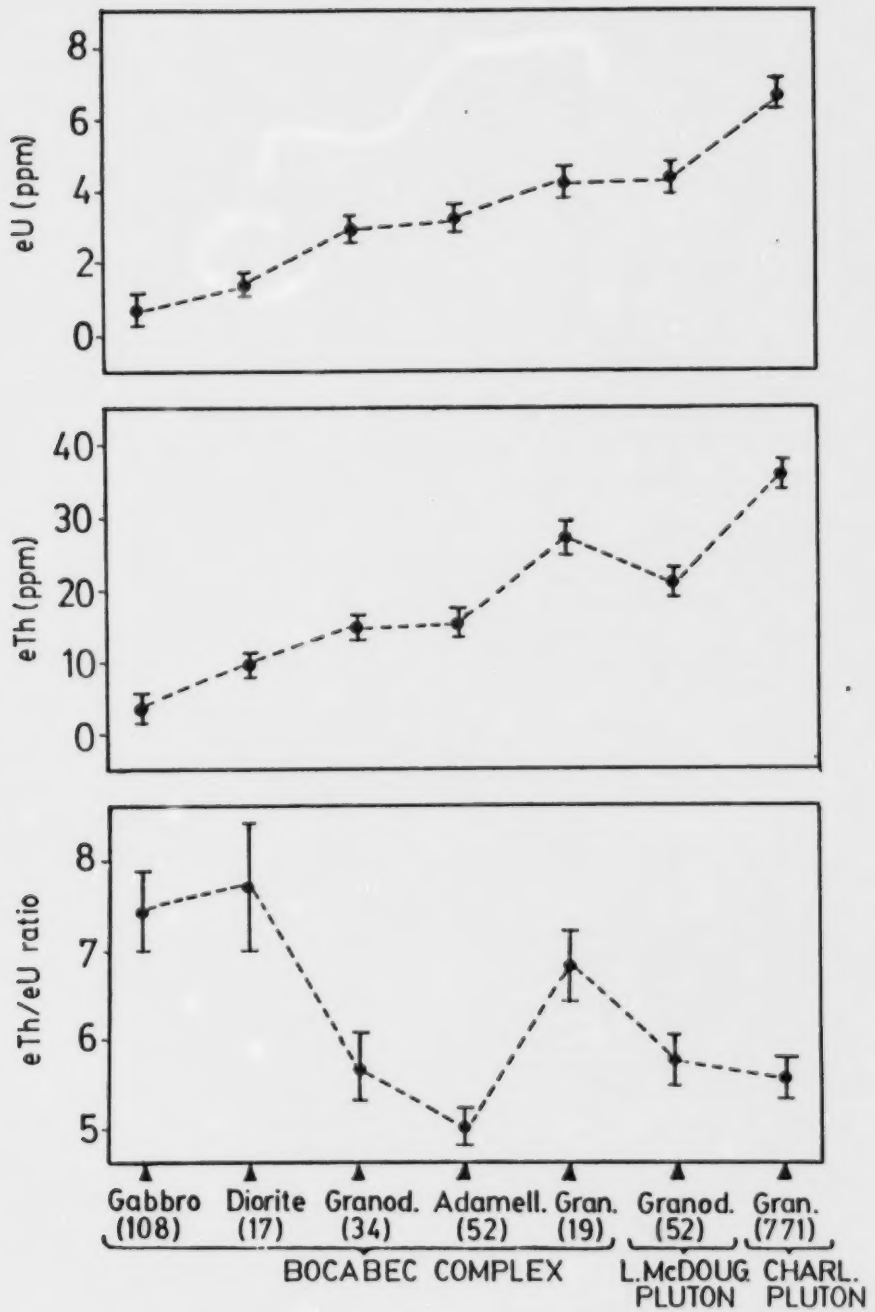


Figure 8. Mean eU, eTh and eTh/U ratio distribution in the Devonian St. George Batholith (number of measurements in parenthesis; bars are standard deviation of the mean).

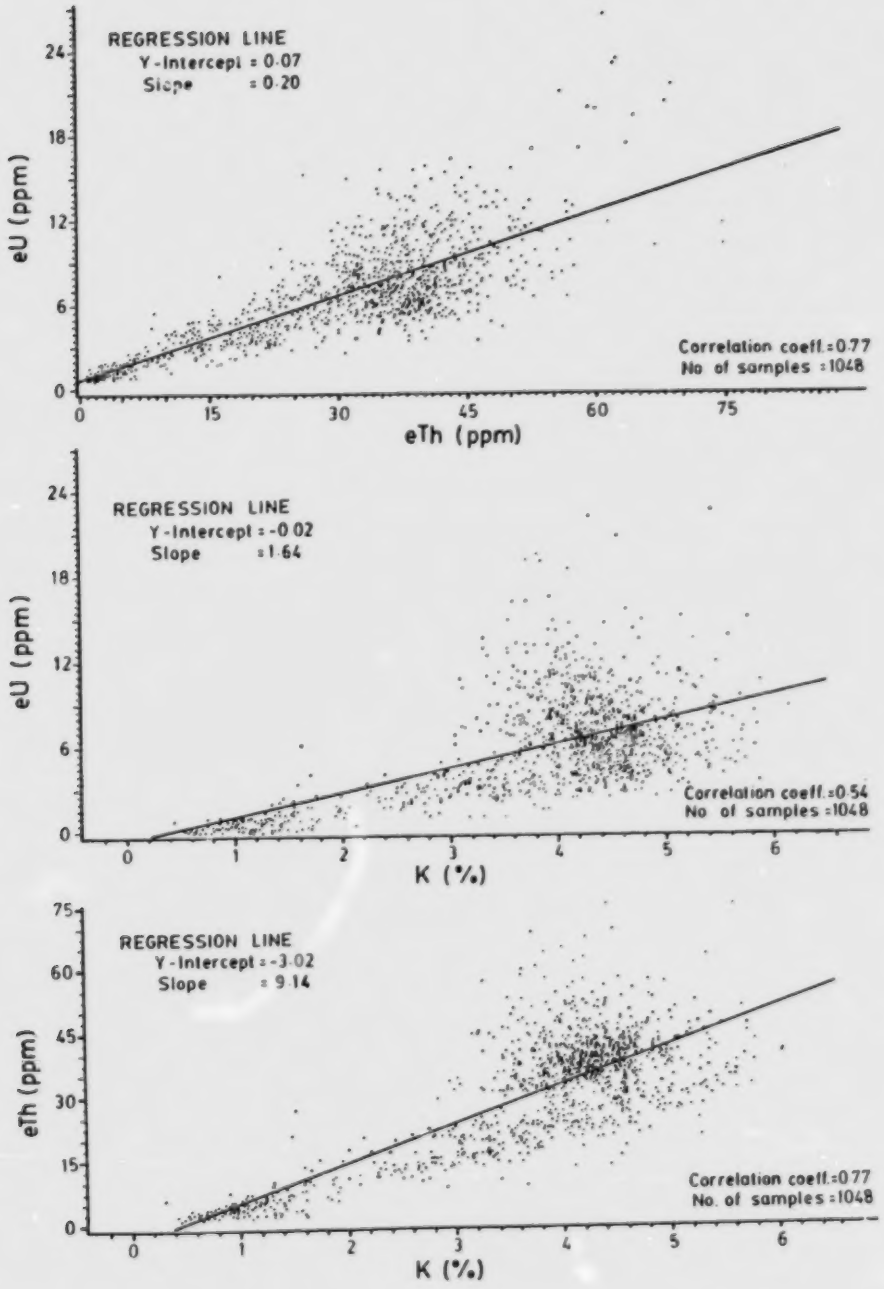


Figure 9. Plots of eU vs. eTh, eU vs. K, and eTh vs. K in the St. George Batholith.

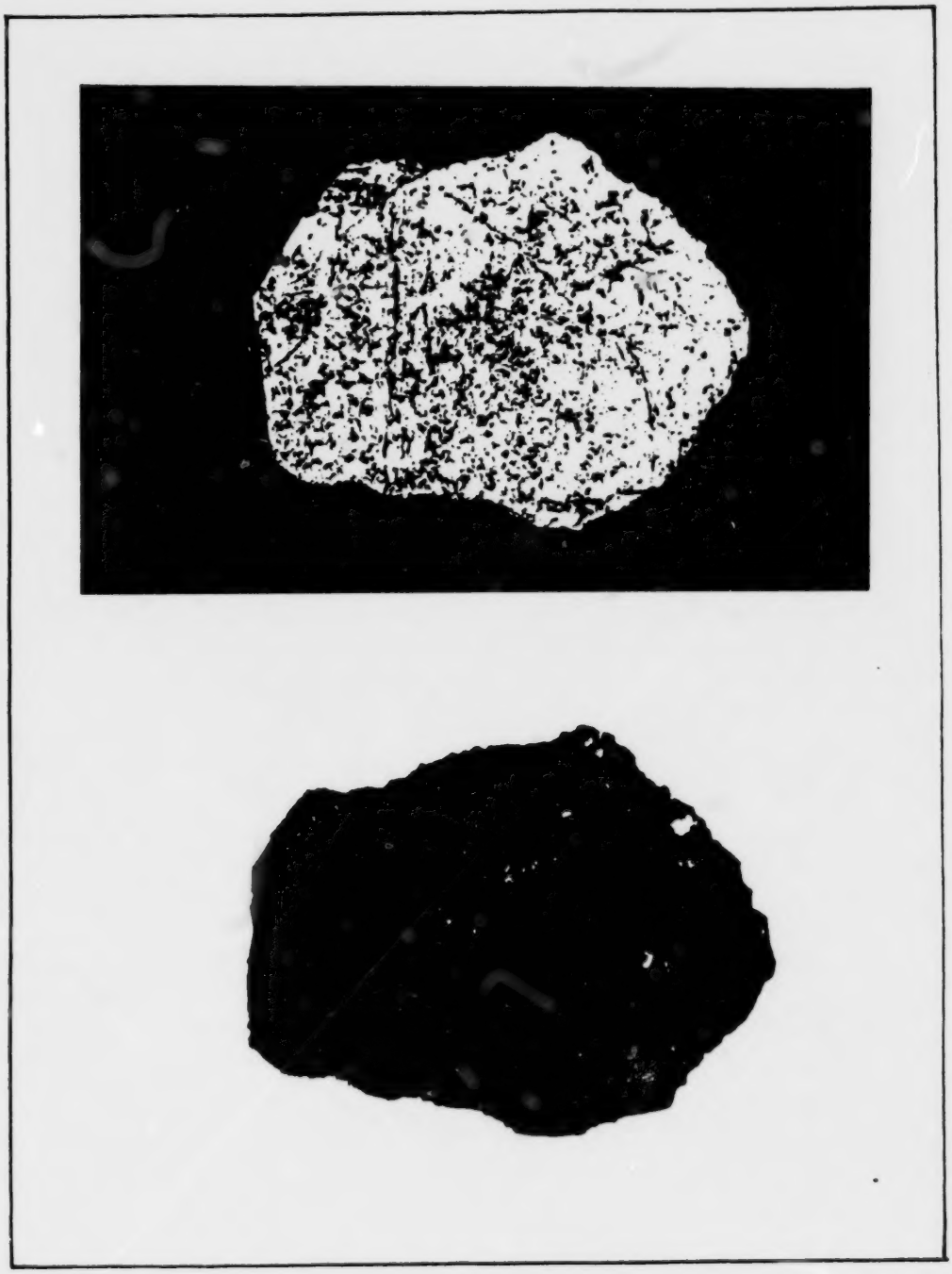


Figure 10. Above: Devonian coarse-grained granite (sample S148/549D; actual size). Below: Surface autoradiograph of granite sample above. Radioactive spots appear bright.

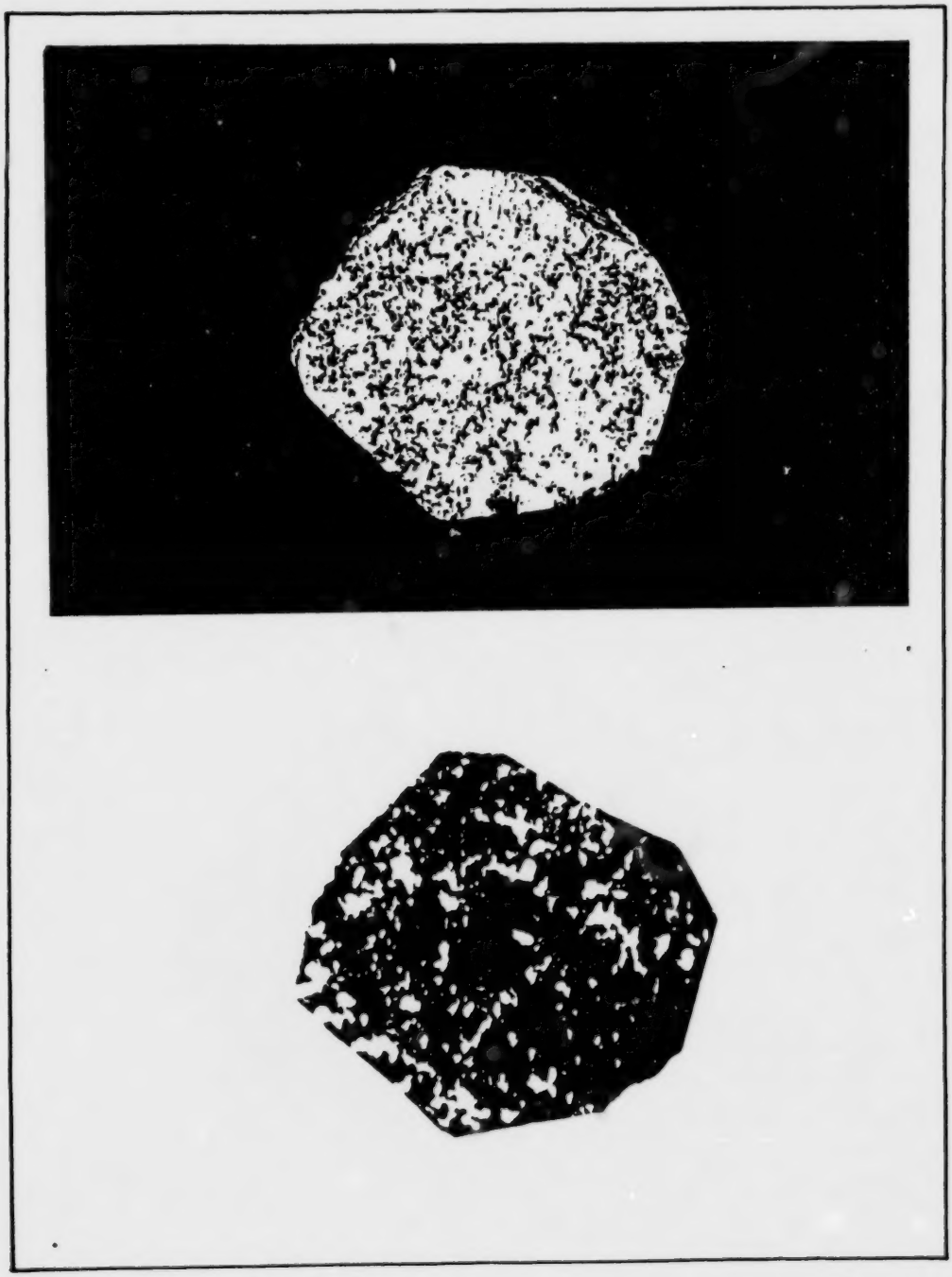


Figure 11. Above: Devonian coarse-grained granite (sample S148/549F; actual size). Below: Surface autoradiograph of granite sample above. Radioactive spots appear bright.

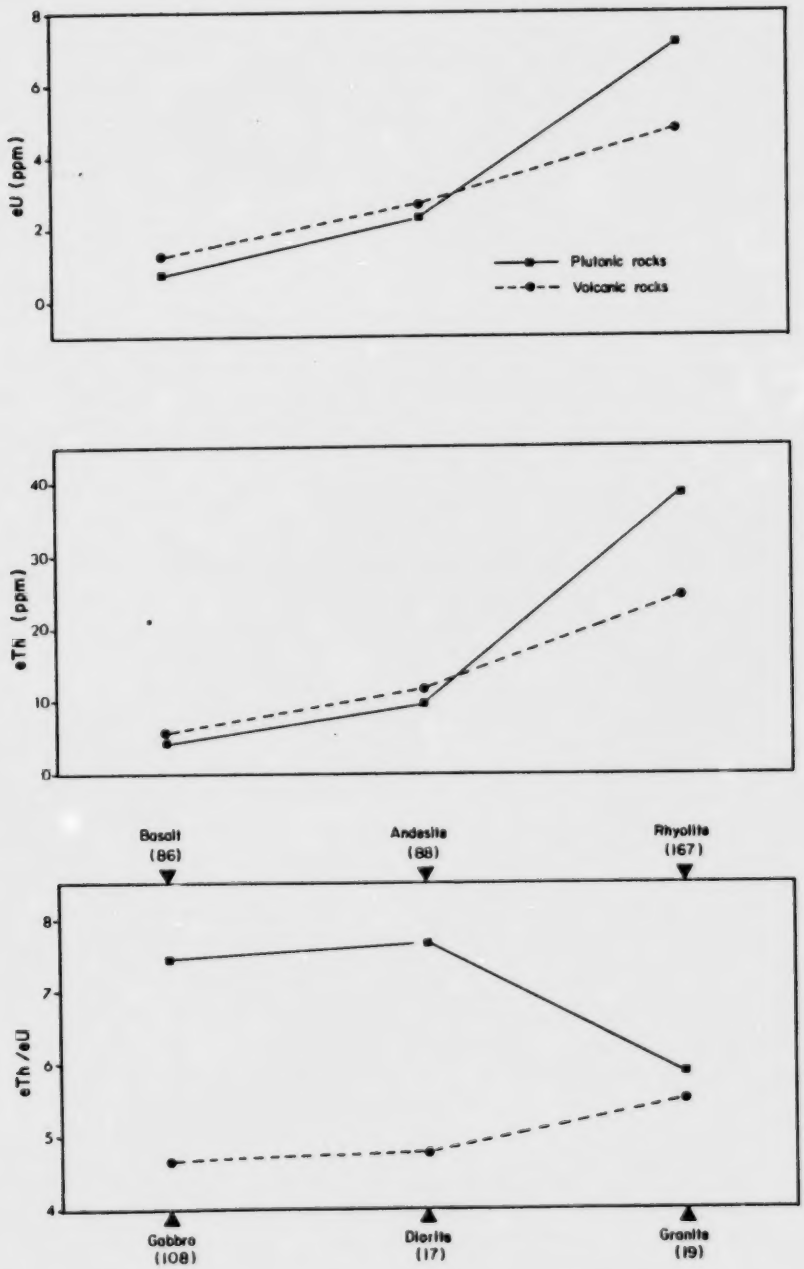


Figure 12. Mean eU, eTh and eTh/eU ratio distribution in the Devonian volcanic and intrusive rocks.

obvious in the mafic and the intermediate rocks, but a marked increase in eU and in eTh is observed in the felsic intrusive member compared to the felsic volcanic member. Moreover, the eU and eTh contents in the mafic and the intermediate volcanic rocks are slightly higher than their counterparts in the intrusive rocks. The eTh/eU ratio increases progressively toward the felsic members of the volcanic evolution. The eTh/eU ratio rises in the intermediate rocks of the intrusive relative to the mafic rocks, but then drops rapidly in the felsic rocks indicating that the U increases relative to Th in the late stage, fluid-rich felsic members of the intrusive suite.

Mississippian

Sedimentary Rocks: In contrast to other sedimentary rocks of the area, the Mississippian sedimentary rocks exhibit no clear relationship between the U and Th content and the grain size. It is possible that these rocks were deposited under alternating oxidizing and reducing conditions. The eTh/eU ratio suggests depletion of U relative to Th in the conglomerate in comparison to the sandstone, siltstone and, to some extent, the shale. Alternatively, U and some of the Th may have been leached from the overlying volcanic rocks, presumably by circulating water, and reprecipitated in the sedimentary rocks to produce the present eU and eTh trends. This suggestion is consistent with both U and Th contents of the Mississippian sedimentary rocks being higher near the contact with the overlying volcanic rocks than at locations distant from the contact. Further support for this idea is given by the same systematic increase in K in the finer-grained rocks (Table 1) as in the other sedimentary rocks of the area. Potassium is more resistant to leaching by circulating water than U and Th and hence little K is expected to have been transported to the sedimentary rocks from the volcanic rocks.

Volcanic Rocks: The eU and eTh contents of the Mississippian volcanic rocks, arranged according to their relative ages, suggest that eU increases with the inferred age of the rocks (Figure 13). The eTh content is erratic, but a systematic increase in eTh/eU ratio in younger rocks is indicated. These data suggest that U has been leached from the younger rocks and redeposited as secondary minerals within the same rocks or in adjacent rocks.

Exceptionally high eU and eTh contents were determined in the rhyolitic ash-flow tuff, ash-fall tuff and lava flow (Table 1). Several zones of epigenetic uranium concentration were found in these rocks at Cherry Hill, Manners Sutton, and York Mills (Plate 86-213).

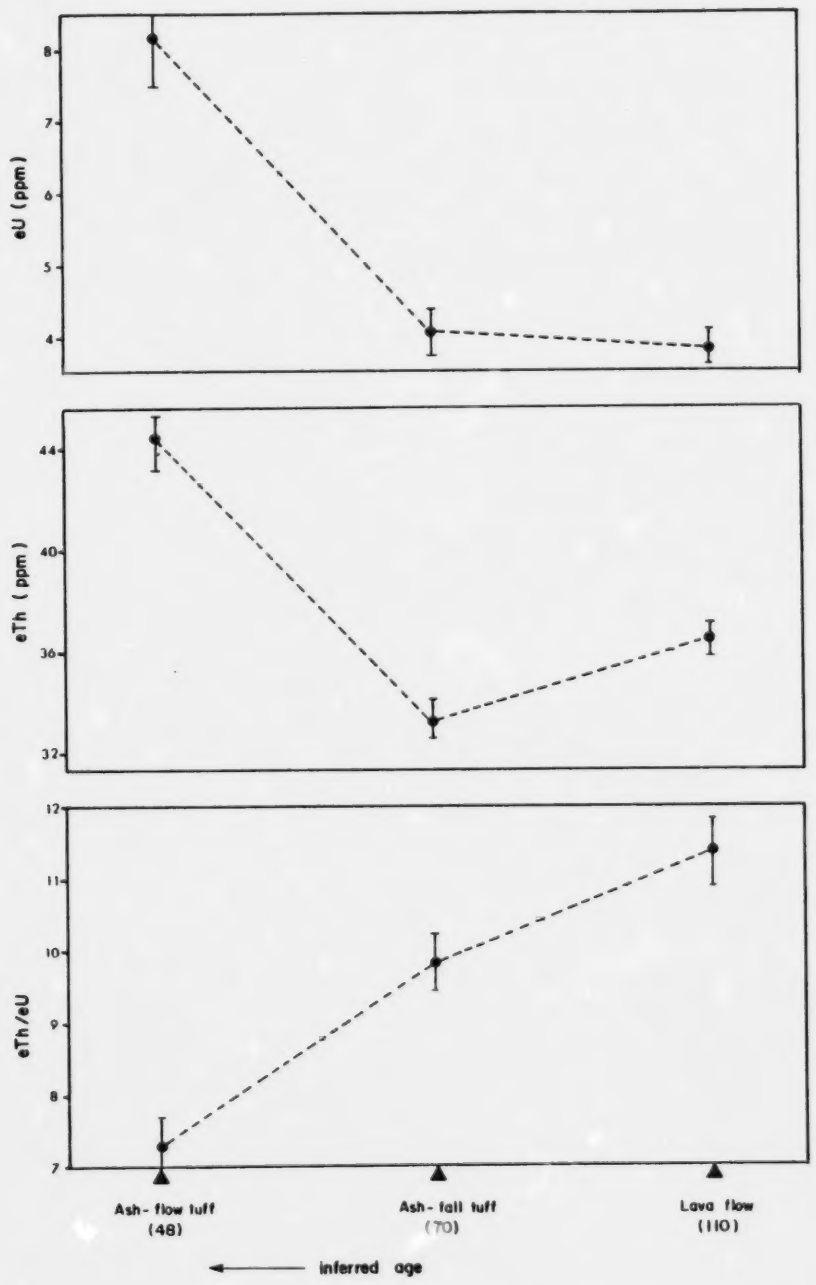


Figure 13. Mean eU, eTh and eTh/eU ratio distribution in the Mississippian volcanic rocks.

Field inspection of these mineralized zones reveals few common features and it is probable that they were formed by different mechanisms such as by supergene and hydrothermal processes.

Radioactivity levels as high as 749 ppm eU and 142 ppm eTh were detected from an area of about 3 km^2 in the rhyolite lava flow located at Manners Sutton (Map Plate 86-213). The U mineralization occurs as black, powdery pitchblende along fractures cross-cutting the lava flow and is spatially related to iron-oxide staining in the lava flow. The radioactive 'spots' on the autoradiograph of sample S148/220D (Figure 14) collected in this zone were identified by X-ray diffraction and found to contain both uraninite, U_3O_8, and uranospinite, $Ca(UO_2AsO_4)_2 \cdot 10H_2O$. Uranospinite, a secondary uranium mineral that is derived from the alteration of uraninite and primary arsenides (Frondel, 1958), was previously identified in the same portion of the study area by the Geological Survey of Canada (Gross, 1957). Although it is possible that the U was derived internally from the volcanic pile by leaching, transportation, and redeposition, its derivation from a nearby external source (e.g., the Devonian Pokiok Batholith or the Silurian metasedimentary rocks) should not be overlooked. A solution to this problem requires a more extensive sampling of rocks than is now possible from the poorly exposed outcrops.

At York Mills, uranium compounds were deposited along a fault plane intersecting the rhyolite ash-fall tuff, where readings of up to 86 ppm eU have been obtained. The intense chloritization in the vicinity of U mineralization may have served as a mechanism to release part of the U from the ash-fall. Because the U content of the fresh parts of the ash-fall tuff is higher than that of the altered part, it is suggested that part, if not all, of the U may have been leached from the ash-fall tuff rhyolite itself.

Minor uranium minerals are found in a well-exposed section at Harvey Station near the railway intersection with Harvey Lake. A geologic cross section of this zone is shown in Figure 15. Here, uranium occurs in the red-stained paleosoils of the Harvey Member, in the carbonate layer of the underlying York Mills Member and along the angular unconformity between these two members. It is likely that U in this zone is derived from the leaching of the upper and lower rhyolitic ash-flow sheets. The autoradiograph of sample S148/212B (Figure 16) taken from the rhyolitic ash flow indicates that these rocks contain U in crystals. This may suggest that the rhyolite ash flow is a possible source for U mineralization in the paleosoil and along the unconformity.

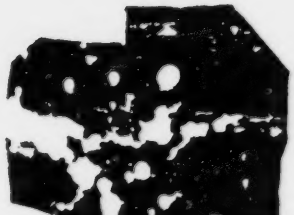


Figure 14. Above: Mississippian lava-flow rhyolite (sample S148/220D; actual size). Below: Surface autoradiograph of rhyolite sample above. Radioactive spots appear bright.

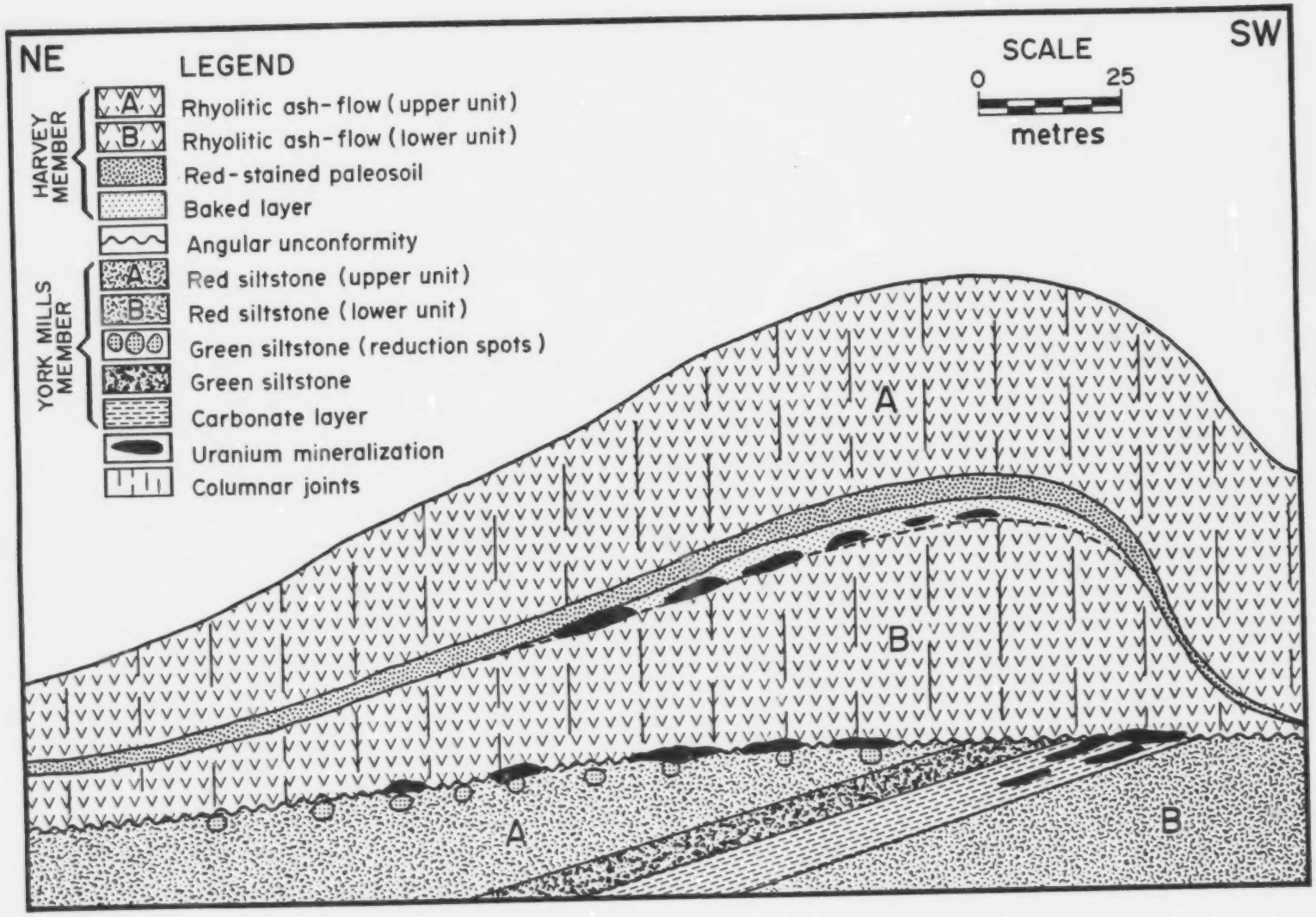


Figure 15. Cross section illustrating the stratigraphic sequence through the Carboniferous rocks of Harvey Station.

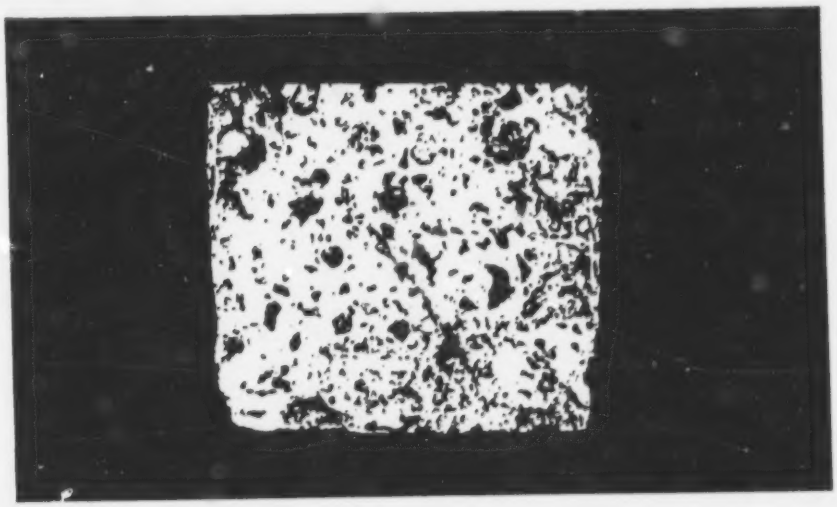


Figure 16. Above: Mississippian ash-flow rhyolite (sample S148/212B; actual size). Below: Surface autoradiograph of rhyolite sample above. Radioactive spots appear bright.

Equivalent U and, to a lesser extent, eTh increase gradually from top to bottom of both the upper and lower rhyolitic ash-flow sheets (Figure 17). This suggests that U may have been leached during weathering of the ash-flow rhyolite. Weathering is likely to have been more intensive in the upper portion of the ash-flow sheet. Weathering by downward percolating water could yield large quantities of the uranyl ion, which could then be transported along columnar joints developed in these rocks and redeposited in the paleosoil, the unconformity and in the carbonate layer.

The paleosoil is characterized by fine-grained clay minerals and organic matter (?) which would serve to adsorb U. The unconformity surface is also a suitable site for mineralization because U-bearing water could move along it and be reduced by organic material derived from vegetation that may be preserved on the paleosurface. High radioactivity is found primarily in 'reduction spots' in siltstone. Part of the U leached from the ash-flow layers is probably redeposited in the underlying sedimentary rocks, particularly in the carbonate layer.

Mississippian/Pennsylvanian

The eU, eTh and K distribution of the Mississippian/Pennsylvanian sedimentary rocks differ from those of the older sedimentary rocks discussed above. In the Mississippian/Pennsylvanian sedimentary rocks, mean eU, eTh and K contents are higher in the coarse-grained varieties than in the fine-grained ones (Table 1). It is possible that U, Th and K are associated with heavy minerals abundant in the coarser-grained sedimentary rocks.

Pennsylvanian

The Pennsylvanian sedimentary rocks are characterized by low eU and eTh contents. Both the conglomerates and the sandstones have almost the same mean eU, eTh and K content. The low radioelement content in these rocks relative to other sedimentary rocks in the area could be related to an oxidizing environment prevailing during their deposition and also to the high rate of water flow through the highly porous Pennsylvanian sedimentary rocks. It is possible also that these rocks were derived from a source with low U and Th contents.

The Pennsylvanian granite of Chance Harbour is also characterized by low eU and eTh. The eTh/eU ratio in the Chance Harbour granite is 8.65 $\pm$ 0.54 which suggests either a considerable depletion of U relative to Th in these rocks, or, more likely, that these rocks were derived from a source magma depleted in U and Th but with Th proportionally more abundant than U. The eU and eTh contents in the Chance Harbour granite are similar to those of Ordovician age.

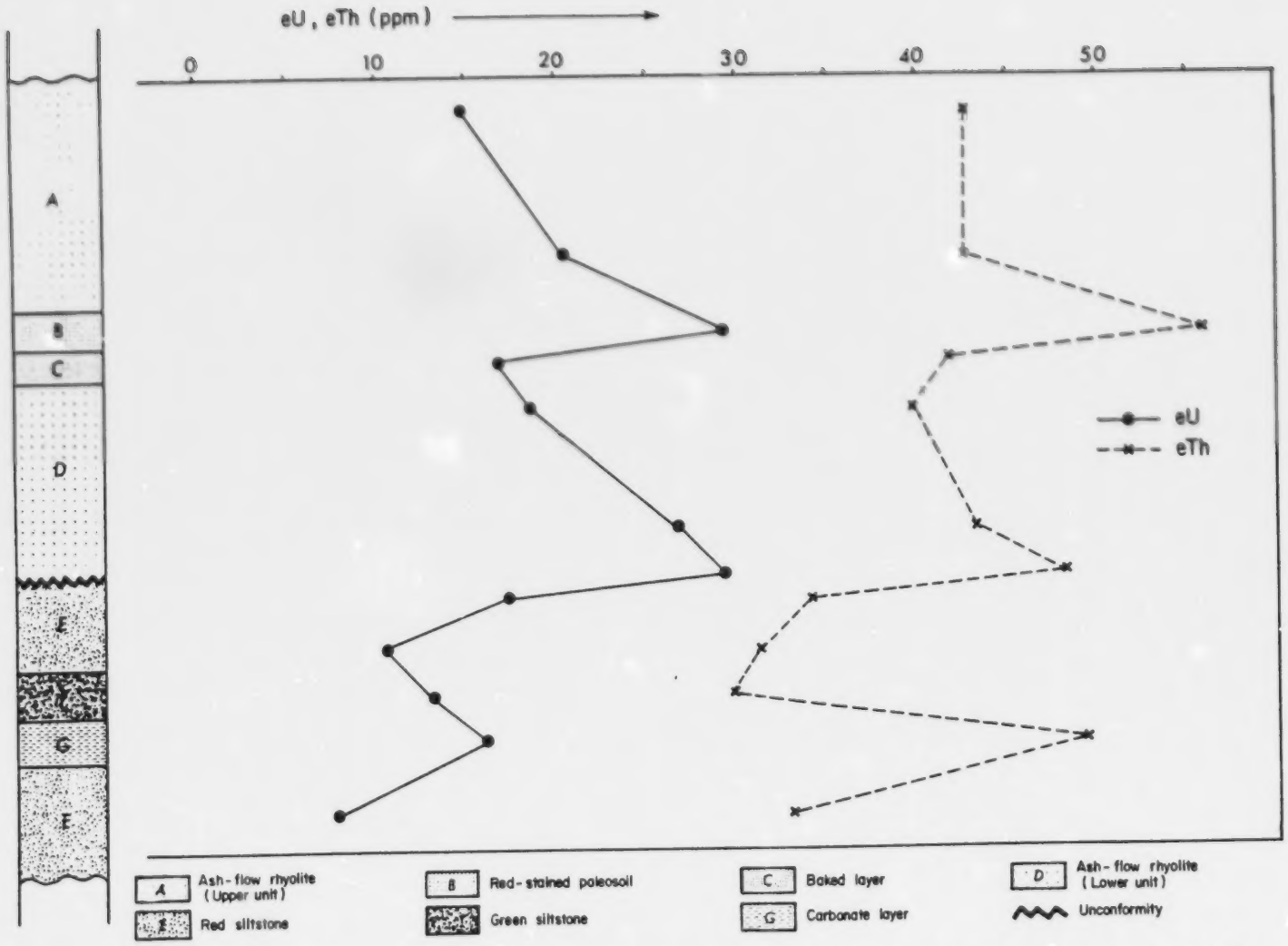


Figure 17. Variation in eU and eTh along the Mississippian volcanic and sedimentary rocks of Harvey Station area.

TRENDS IN URANIUM AND THORIUM ABUNDANCES WITH GEOLOGIC TIME

Because of the scarcity of radiometric dates and uncertainty of relative age determinations for rock units in the study area, only relative ages are used in considering trends of eU and eTh distribution with geologic time.

The significance of differences in the mean eU and eTh content of the rocks of various ages was tested statistically by Students t-test. The difference in mean content of eU or eTh in two sets of data becomes statistically significant when the calculated 't-value' of the two data sets falls beyond the theoretical 't-value' for a certain level of significance. A 95% confidence limit ($\alpha = 0.05$) is used for the test.

Sedimentary Rocks

The mean eU content of sedimentary rocks increases from Precambrian to Silurian (Figure 18). The mean eTh increases from Precambrian to Ordovician but decreases slightly in the Silurian sedimentary rocks. There is a slight decrease in both eU and eTh for Devonian rocks relative to those of Silurian age. The highest contents of both eU and eTh occur in the Mississippian rocks; there is a marked decrease in both eU and eTh in the Pennsylvanian sedimentary rocks. The eTh/eU ratio decreases from the Precambrian through Devonian but increases in the Mississippian and then decreases slightly in the Pennsylvanian sedimentary rocks.

The results of the t-test performed on the eU and eTh distributions in these rocks indicate that there are statistically significant differences in the mean eU and eTh contents of sedimentary rocks of different ages, except in eU contents of Silurian and Devonian and eTh content of Ordovician, Silurian, and Devonian sedimentary rocks.

Rhyolitic Rocks

The mean eU and eTh contents of the rhyolitic rocks increase from the Precambrian through Devonian to the Mississippian rhyolitic rocks (Figure 19). The eTh/eU ratio decreases slightly from the Precambrian to Devonian and increases rapidly from Devonian to Mississippian.

A statistically significant difference in eU and eTh contents in the rhyolitic rocks of different ages is indicated from the results of t-test except for the eU content in the Devonian and Mississippian rhyolites.

Dostal *et al*. (1983) have investigated the U, Th and K contents of Paleozoic rhyolites in Nova Scotia and observed that the average abundances increase systematically in the following

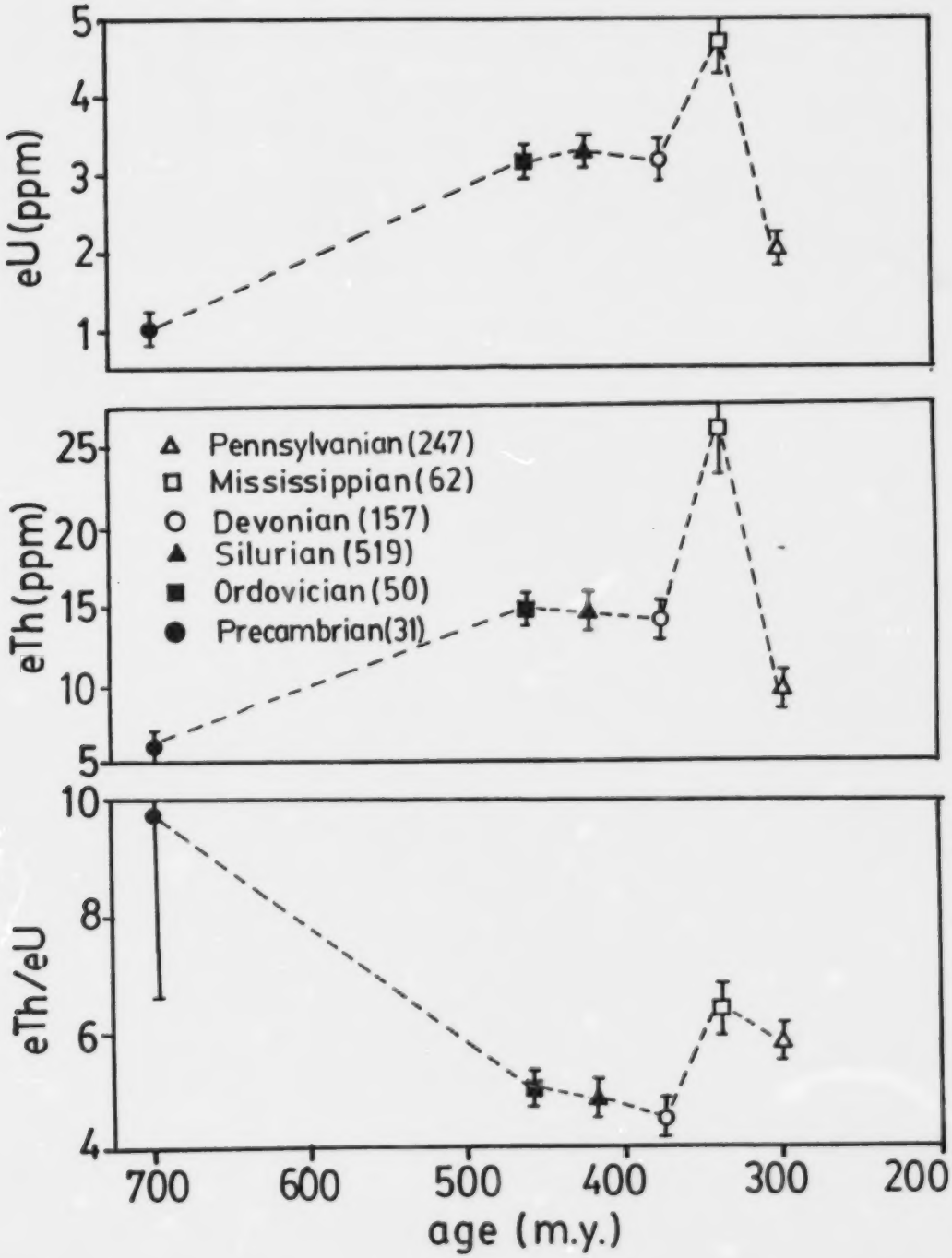


Figure 18. Mean eU, eTh and eTh/eU ratio distribution in the metasedimentary and sedimentary rocks of various ages (number of measurements in parentheses; bars are standard deviation of the mean).

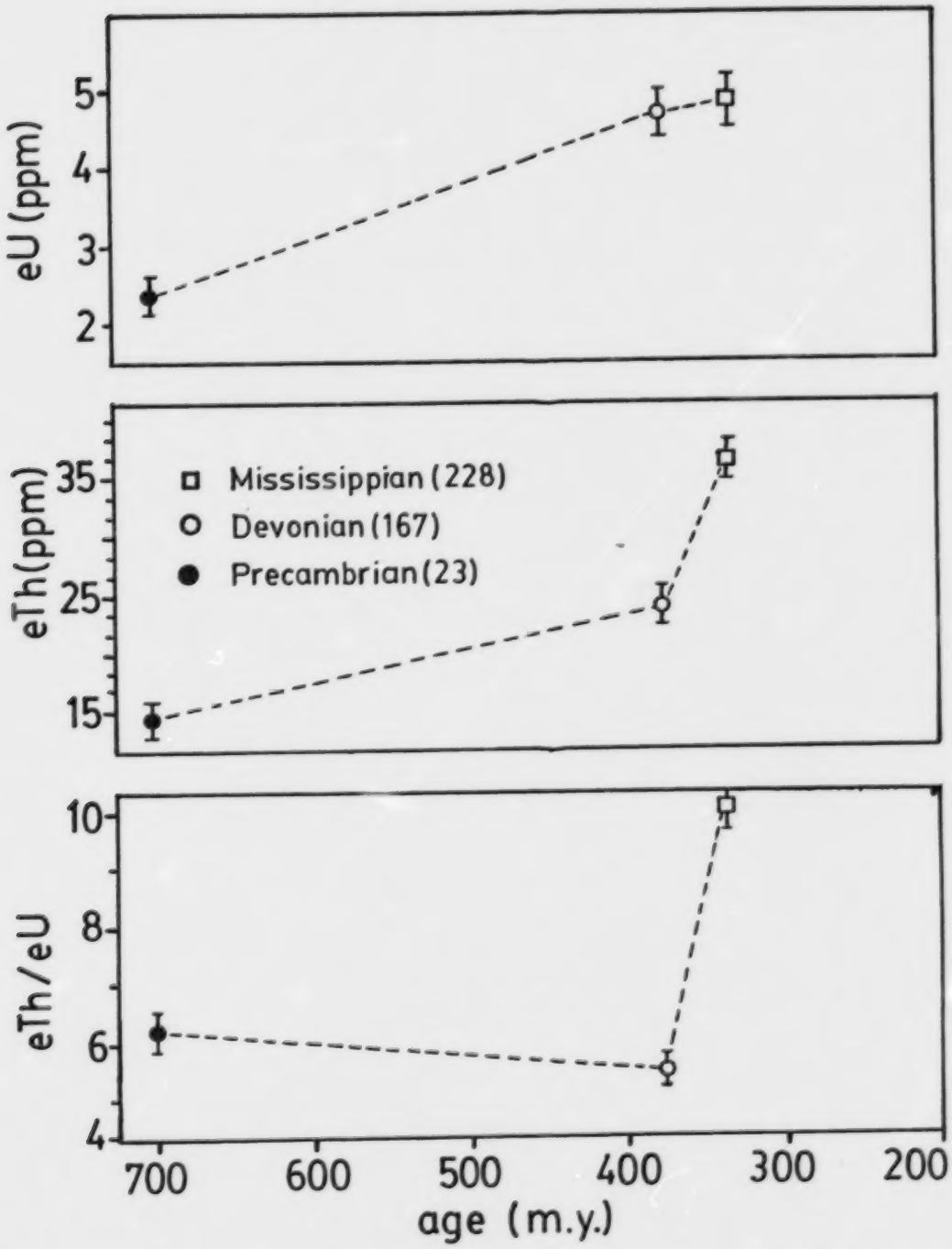


Figure 19. Mean eU, eTh and eTh/eU ratio distribution in rhyolitic rocks of various ages (number of measurements in parentheses; bars are standard deviation of the mean).

order: Cambrian, Silurian and Devono-Carboniferous. The depletion of U, Th and K in older rocks is attributed to secondary processes such as metamorphism.

Granitic Rocks

The mean eU and eTh contents of the granitic rocks increase from Precambrian to Devonian (Figure 20). An obvious decrease in both eU and eTh contents takes place in the Pennsylvanian granite relative to the Devonian granitic rocks. However, the erratic trend of eTh/eU ratios in rocks of these ages suggests a complex history due to depletion of U relative to Th in Ordovician rocks.

The t-test on the granitic rocks of various ages indicates a statistically significant difference in both eU and eTh contents among these granites, but the test failed to differentiate between the Ordovician and Pennsylvanian granites on the basis of their eU and eTh contents.

The increase in U and Th abundances with decreasing age of the rock units may lead to the generation of uranium metallogenic provinces. Similar patterns were recognized in the Caledonian Fold Belt of East Greenland calc-alkalic granite (Neilsen and Steenfelt, 1977; Steenfelt, 1982), where higher uranium concentrations are associated with the Devonian granite than most of the earlier Caledonian and older granites. Uranium mineralization along fractures and in hydrothermally altered rocks were formed in the Devonian granite of East Greenland.

In Russia, an area of 60,000 km^2, containing sites of U, U-Th, and REE(rare earth element)-Th mineralization, as well as deposits of these elements, was surveyed by gamma-ray spectrometry to identify potential source rocks for U and Th (Boltneva et al., 1964; quoted after Kogan et al., 1971). The area contains five granitoid intrusions of different ages: M. Devonian - L. Ordovician; M. Ordovician - U. Ordovician; M. Devonian - U. Devonian; U. Devonian - L. Carboniferous; and U. Carboniferous - Permian. The result of this investigation shows a regular increase in the concentration of U, Th and REE from old to young intrusions in ore-bearing regions. In the barren area, both U and Th generally decrease from old to young intrusions.

DISTRIBUTION OF MAJOR AND TRACE ELEMENTS (INCLUDING URANIUM AND THORIUM) IN IGNEOUS ROCKS

About 125 samples of intrusive and extrusive rocks from southwestern New Brunswick have been analyzed by neutron

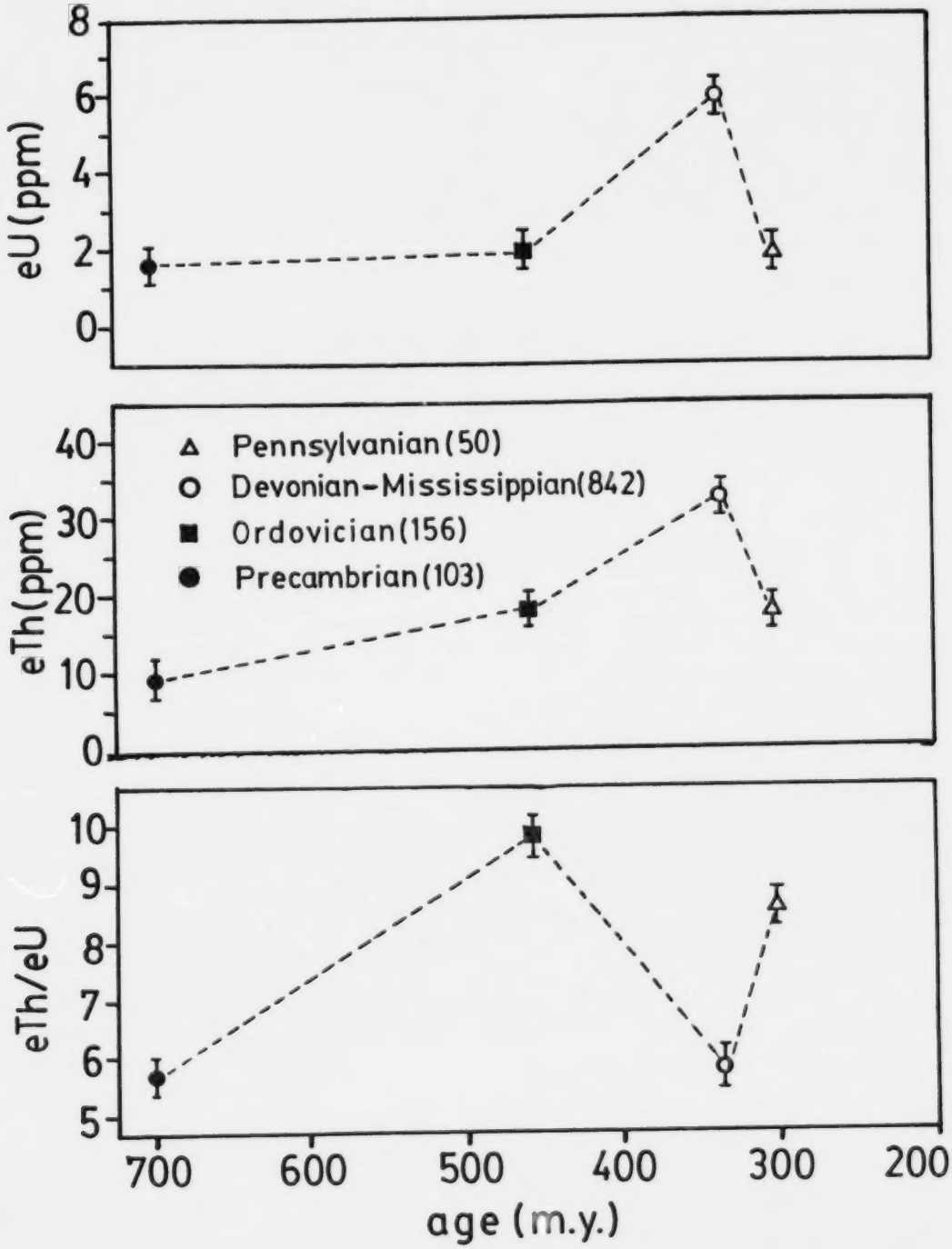


Figure 20. Mean eU, eTh and eTh/eU ratio distribution in granitic rocks of various ages (number of measurements in parentheses; bars are standard deviation of the mean).

activation techniques for uranium and thorium. The abundances of uranium and thorium as well as analyzes for major, some minor and trace elements, are summarized in Table 2. The samples are representative of the St. George Batholith (Charlotte Pluton and Bocabec Intrusive Complex), eight granitic stocks (Beech Hill, Sorrel Ridge, Milltown, Eagle Lake, Pleasant Ridge, Tower Hill, South Oromocto Dyke, Mohannas and Musquash) and the volcanic rocks of the Mount Pleasant area.

Correlation coefficients between uranium and thorium and various major, minor and trace elements were tested statistically for their significance at 90, 95 and 99% confidence levels (i.e., $\alpha = 0.10$, 0.05 and 0.01, respectively). Then, according to this test the strength of correlation between two elements is ranked into poor, moderate and good (for more detail refer to Hassan, 1984).

ST. GEORGE BATHOLITH

The average abundances of major, minor and trace elements, including U and Th, in the rocks of the St. George Batholith are given in Table 2. These rocks range in composition from diorite(approx. 52 wt. % SiO_2) to aplite (approx. 76 wt. % SiO_2). In general, both U and Th increase approximately nine-fold from the mafic to the felsic rocks; U ranges from 1.04 ppm in the diorite to 9.66 ppm in the aplite and Th rises from 4.20 ppm in the diorite to 36.83 ppm in the aplite. The increase is not regular because tonalite has higher U and Th contents than the granodiorite, although the latter is more felsic. However, this apparent anomaly may be the result of inadequate sampling of the tonalite: only one sample was analyzed.

The rocks of the St. George Batholith are calc-alkaline (Figure 21) and peraluminous to metaluminous (the ratio of the molecular proportions of $Al_2O_3/CaO+Na_2O+K_2O$ ranges from 0.96 to 1.15 and averages 1.05 for rocks of the Charlotte Pluton; the Bocabec Intrusive Complex is largely metaluminous). They have chemical characteristics typical of calc-alkalic granites, such as those of the southern California, Sierra Nevada, and Idaho Batholiths, in that both U and Th trends with SiO_2 content fall within the zone defined by other calc-alkalic rocks on Figure 22 (adapted from Tilling and Gottfried, 1969).

The scatter of U vs. Th (Figure 23) displays a strong positive linear relationship (correlation coefficient between U and Th for the St. George Batholith is 0.85) which suggests a similarity in behaviour between U and Th during magmatic evolution. The relationship between the U and Th is less obvious in the late stages of magma differentiation than the earlier stages, particularly in the eastern end of the batholith. The statistical correlation coefficient between U and Th is equal to 0.89 for

Table 2.
Mean and Standard Deviation of Abundances of Major, Minor and Trace Elements in Rocks of the St. George Batholith

ELEMENTS	CHARLOTTE PLUTON						BOCABEC COMPLEX							
	APLITE		PORPHYRITIC GRANITE		C.G. GRANITE		ADAMELLITE		GRANODIORITE		TONALITE		DIORITE	
	n	mean	n	mean	n	mean	n	mean	n	mean	n	mean	n	mean
SiO_2 (%)	12	76.06±1.54*	13	75.69±2.83	13	75.41±1.60	2	68.50	17	62.50±2.98	1	61.60	5	52.26±3.29
TiO_2 (%)	12	0.15±0.11	13	0.24±0.14	13	0.17±0.05	2	0.65	17	1.09±0.31	1	0.80	5	1.38±0.24
Al_2O_3 (%)	12	12.79±0.67	13	12.71±0.76	13	12.73±0.60	2	15.85	17	14.52±0.53	1	15.90	5	15.52±1.59
Fe_2O_3 (%)	12	0.55±0.34	13	0.60±0.35	13	0.45±0.24	2	1.45	17	2.28±0.96	1	0.60	5	1.96±0.34
FeO (%)	12	0.72±0.53	13	0.98±0.56	13	0.98±0.27	2	3.20	18	4.64±1.28	1	5.90	5	6.98±1.01
MnO (%)	12	0.03±0.02	13	0.03±0.02	13	0.03±0.01	2	0.13	17	0.16±0.07	1	0.08	5	0.20±0.06
MgO (%)	12	0.13±0.17	13	0.27±0.25	13	0.13±0.08	2	0.60	18	1.73±0.62	1	2.10	5	5.70±1.12
CaO (%)	12	0.45±0.32	13	0.75±0.57	13	0.57±0.17	2	1.90	18	3.90±0.96	1	4.80	5	7.18±2.84
Na_2O (%)	12	3.64±0.37	13	3.31±0.30	13	3.54±0.21	2	4.00	18	4.00±0.42	1	4.80	5	3.22±0.46
K_2O (%)	12	4.84±0.70	13	5.10±0.47	13	4.86±0.21	2	3.25	18	2.45±0.50	1	1.40	5	1.08±0.32
P_2O_5 (%)	12	0.04±0.02	13	0.06±0.04	13	0.04±0.01	2	0.15	17	0.21±0.10	1	0.20	5	0.18±0.11
Sr (ppm)	12	33.37±46.33	13	53.31±47.25	13	24.82±15.30								
Rb (ppm)	12	319.25±99.18	13	305.08±92.17	13	313.46±74.11								
Zr (ppm)	12	151.25±155.15	13	145.23±52.32	13	136.23±54.61								
F (ppm)	4	447.50±702.35	4	305.00±240.07	8	807.50±366.52								
Ni (ppm)	12	11.46±8.01	13	11.54±7.40	12	16.10±7.36								
Cr (ppm)	12	6.39±4.37	13	6.01±2.89	11	6.45±3.14								
Zn (ppm)	12	55.77±58.36	13	28.96±10.05	12	47.72±53.24								
Cu (ppm)	12	5.46±3.00	13	4.73±1.97	11	5.00±1.66								
U (ppm)	12	9.66±5.97	13	7.13±4.35	13	9.05±4.30	2	3.20	18	2.44±0.86	1	2.70	5	1.04±0.62
Th (ppm)	12	36.83±19.29	13	35.69±15.34	13	31.00±10.62	2	12.00	18	10.55±4.25	1	12.00	5	4.20±1.92
Th/U	12	4.09±1.04	13	5.62±1.89	13	3.71±1.12	2	3.80	18	4.37±0.90	1	4.40	5	4.54±1.37

n = number of samples

* error above the mean expressed by the standard deviation.

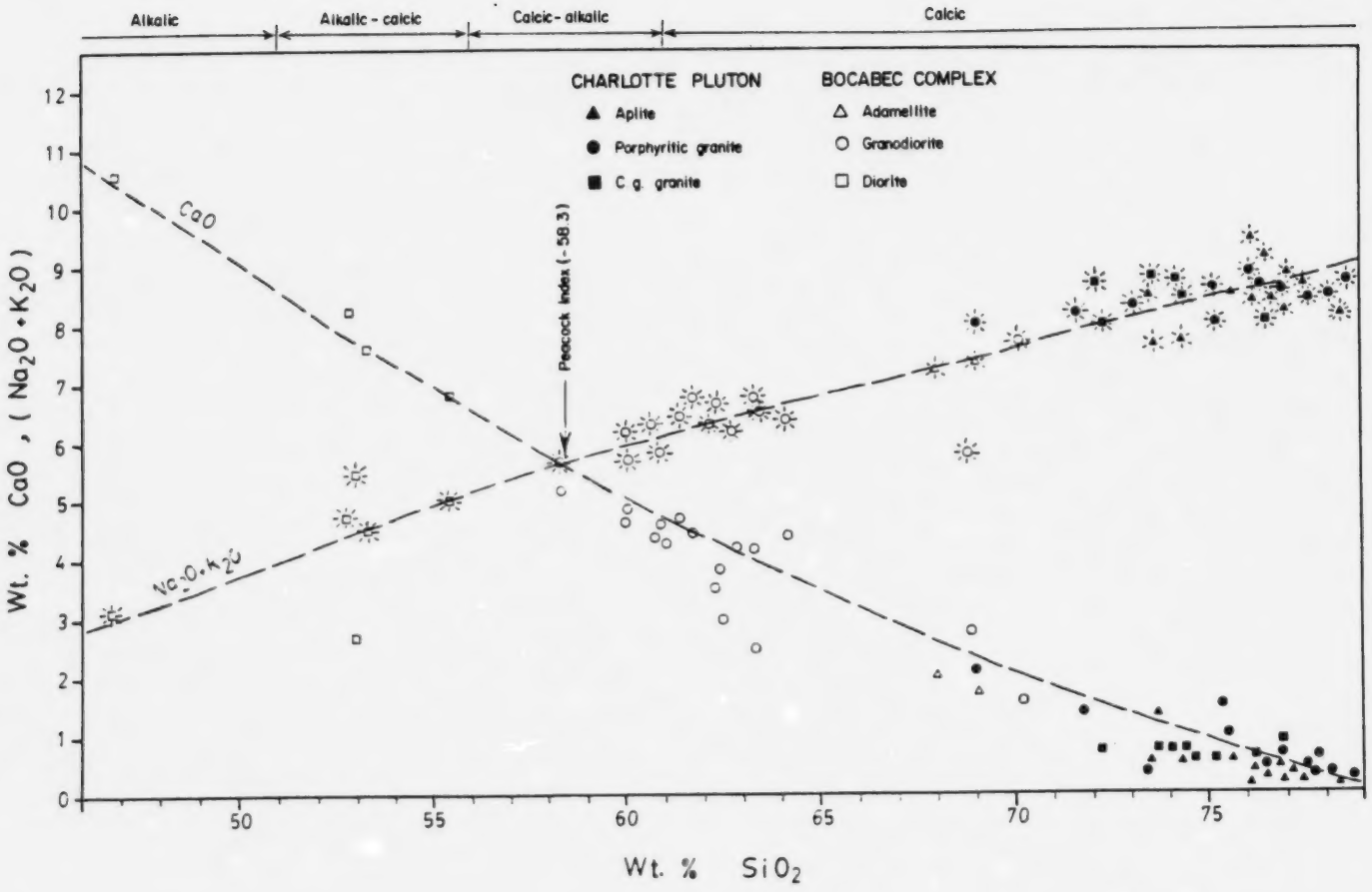


Figure 21. Peacock's variation diagram for rocks of the St. George Batholith.

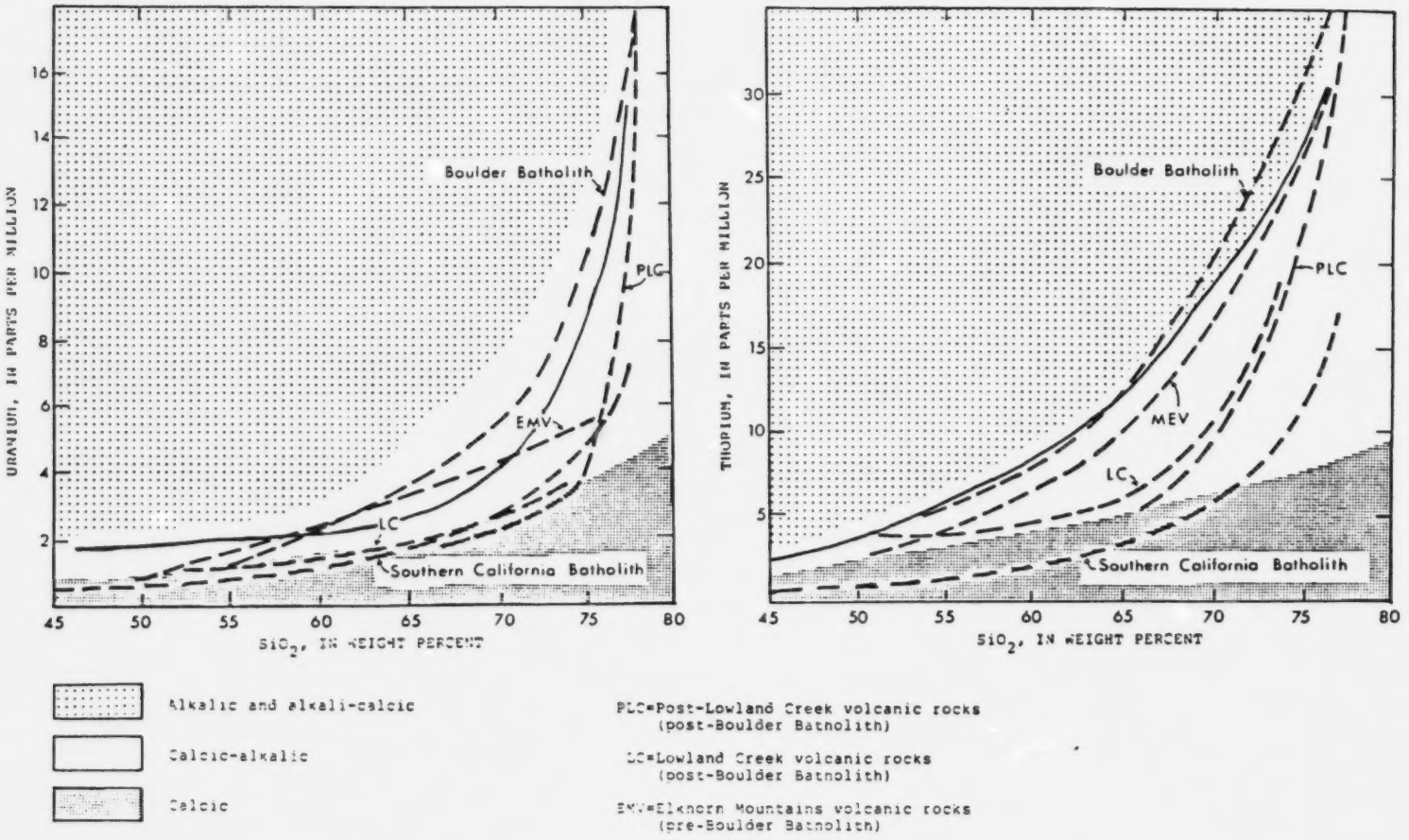


Figure 22. U - SiO_2 and Th - SiO_2 trends for rocks of the St. George Batholith superimposed on selected reference igneous suites.

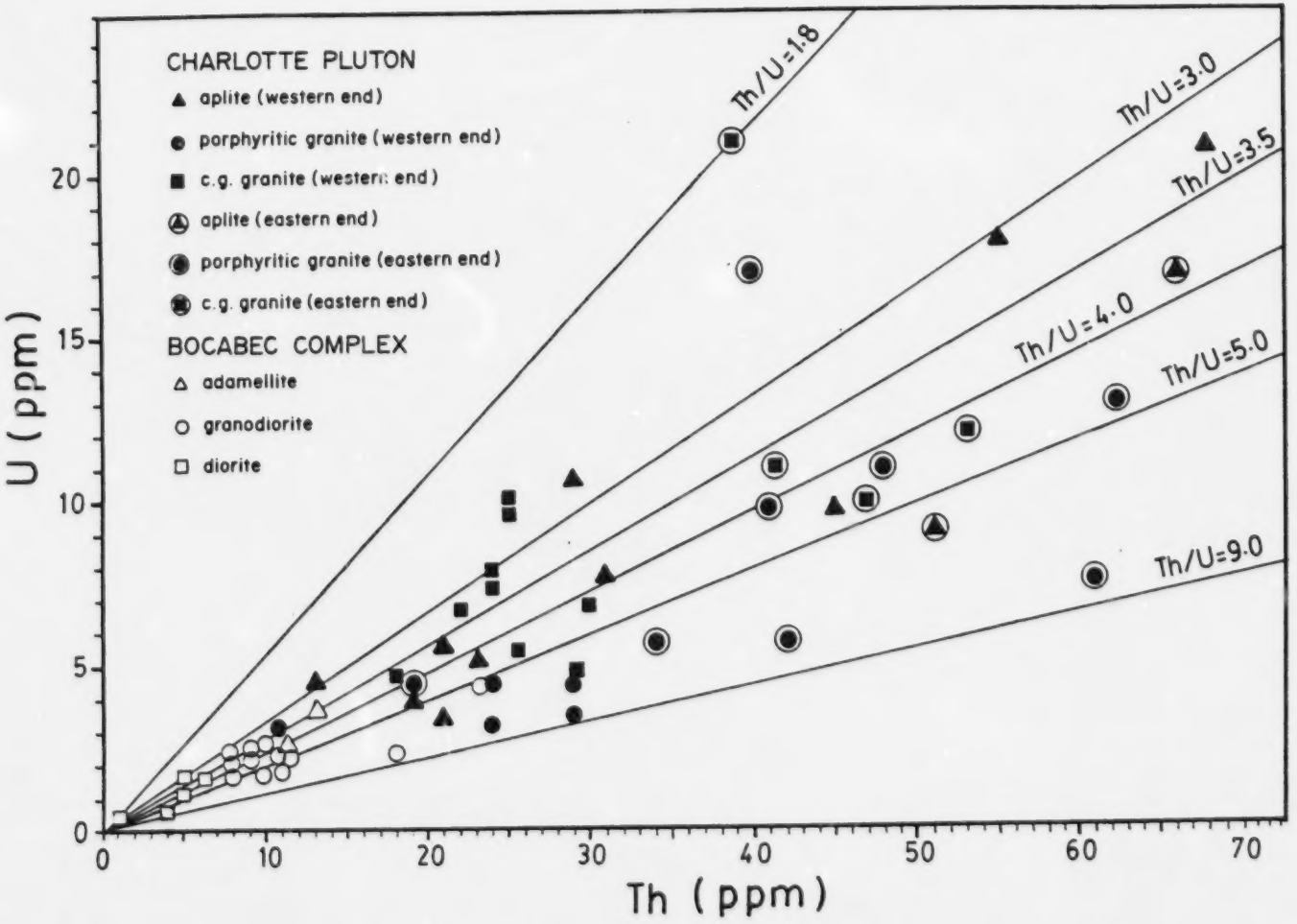


Figure 23. U vs. Th plot for the rocks of the St. George Batholith.

the rocks of the Bocabec Intrusive Complex whereas the correlation coefficient for the rocks of the Charlotte Pluton is 0.73. Furthermore, the correlation coefficient between U and Th is 0.44 in the eastern end of the Charlotte Pluton, in contrast to its western end where the correlation coefficient is 0.87.

The later stages of magmatic differentiation (where SiO_2 content is more than 70%) may be affected by other processes not active in the early stages of magmatic differentiation. These could be secondary processes such as hydrothermal alteration. It appears also that such processes may have affected mainly the eastern end of the batholith (Figure 23), where strong fractionation between U and Th took place. This conclusion is also supported by the broad range of Th/U ratios (1.8 to 9.0) in the samples of the eastern end of the St. George Batholith (Figure 23).

Several compositional indices, including Harker's (SiO_2 content) index, felsic index (Simpson, 1954) and degree of alumina saturation index were investigated with respect to U and Th variation in the different rock types of the St. George Batholith.

Plots of U and Th against SiO_2 content (Harker variation index) are shown in Figure 24. This figure shows an increase of both U and Th in the more felsic rocks. The increase is more obvious in the felsic members where the weight percent of SiO_2 in rock samples is greater than 75%. However, it appears that Th content increases systematically with the more differentiated rocks of the batholith, whereas U content, at the last stage of magmatic evolution, is higher in the coarse-grained granite in contrast to the more differentiated rocks of the porphyritic granite. This suggests that U (highly mobile) was preferentially depleted from the porphyritic granites relative to Th (less mobile).

The plot of the Th/U ratio against SiO_2 content for the various phases of the batholith indicates high variability of Th/U ratio in the last stages of magmatic differentiation (Figure 25). Figure 25 also suggests that U is depleted relative to Th in the porphyritic granites. However, U is enriched relative to Th in the coarse-grained granite and the aplite.

Both U and Th increase with felsic index (100(Na+K)/(Na+K+Ca)) of the rocks (Figure 26), with the exception of a slight decrease in the content of Th in the coarse-grained granite compared to the porphyritic granite. The increase in U with felsic index is more systematic than in Th, if the degree of differentiation is considered.

The comparison of U and Th contents with degree of alumina saturation (Figure 27) reveals lack of clear relationships between these variables for similar rock types. However,

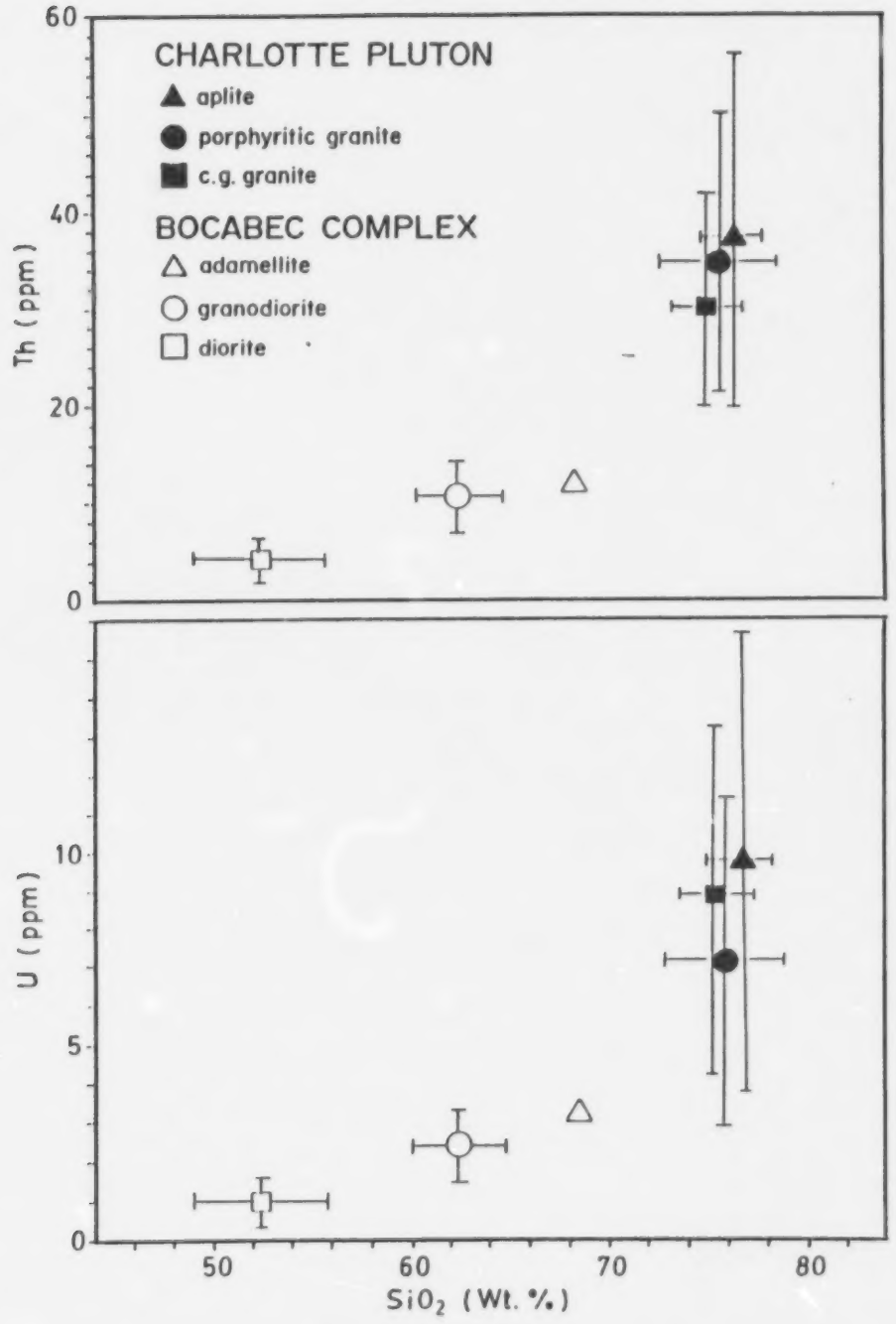


Figure 24. U and Th vs. SiO_2 for the rocks of the St. George Batholith (bars are standard deviation of the mean).

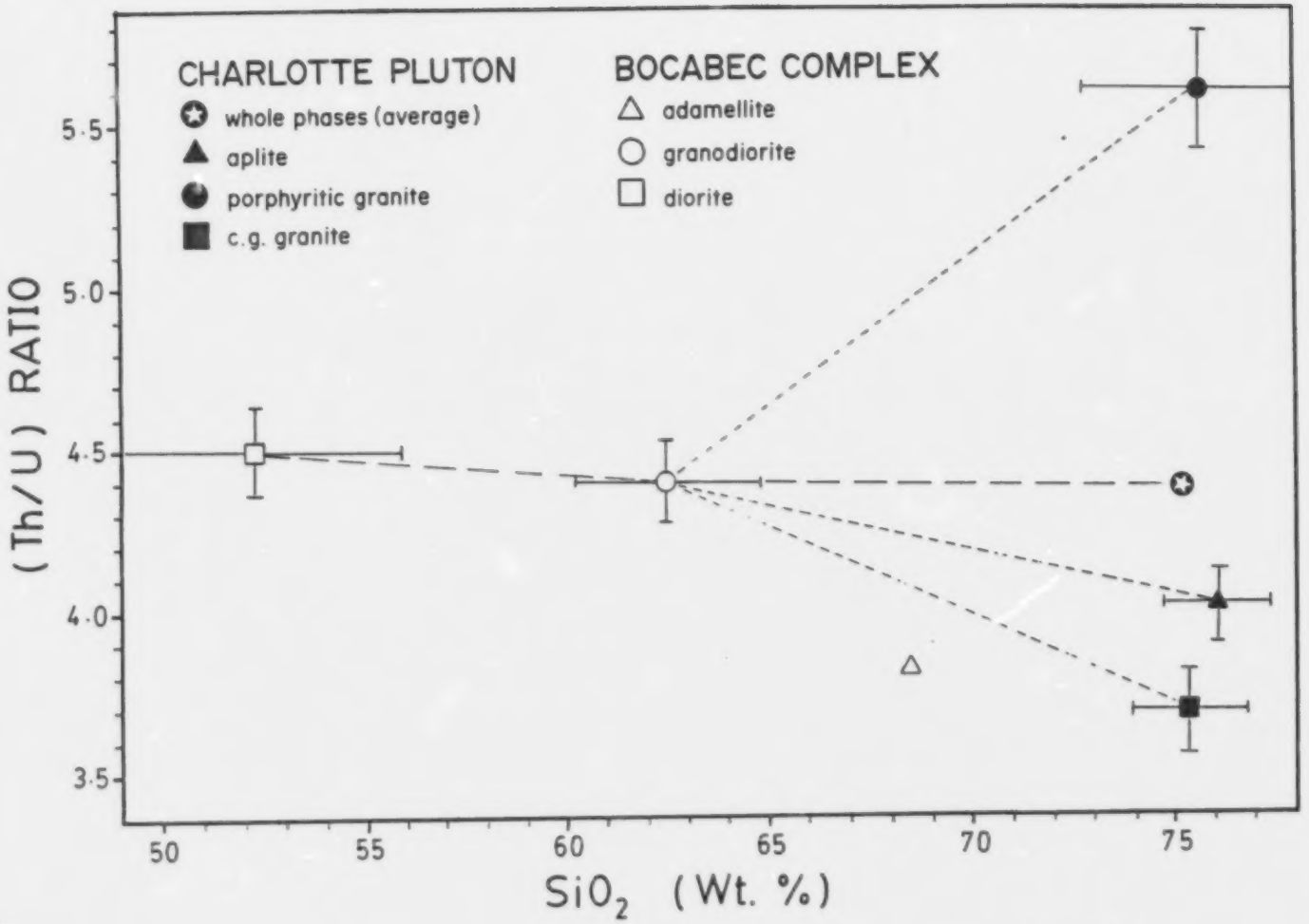


Figure 25. Th/U ratio vs. SiO_2 for rocks of the St. George Batholith.

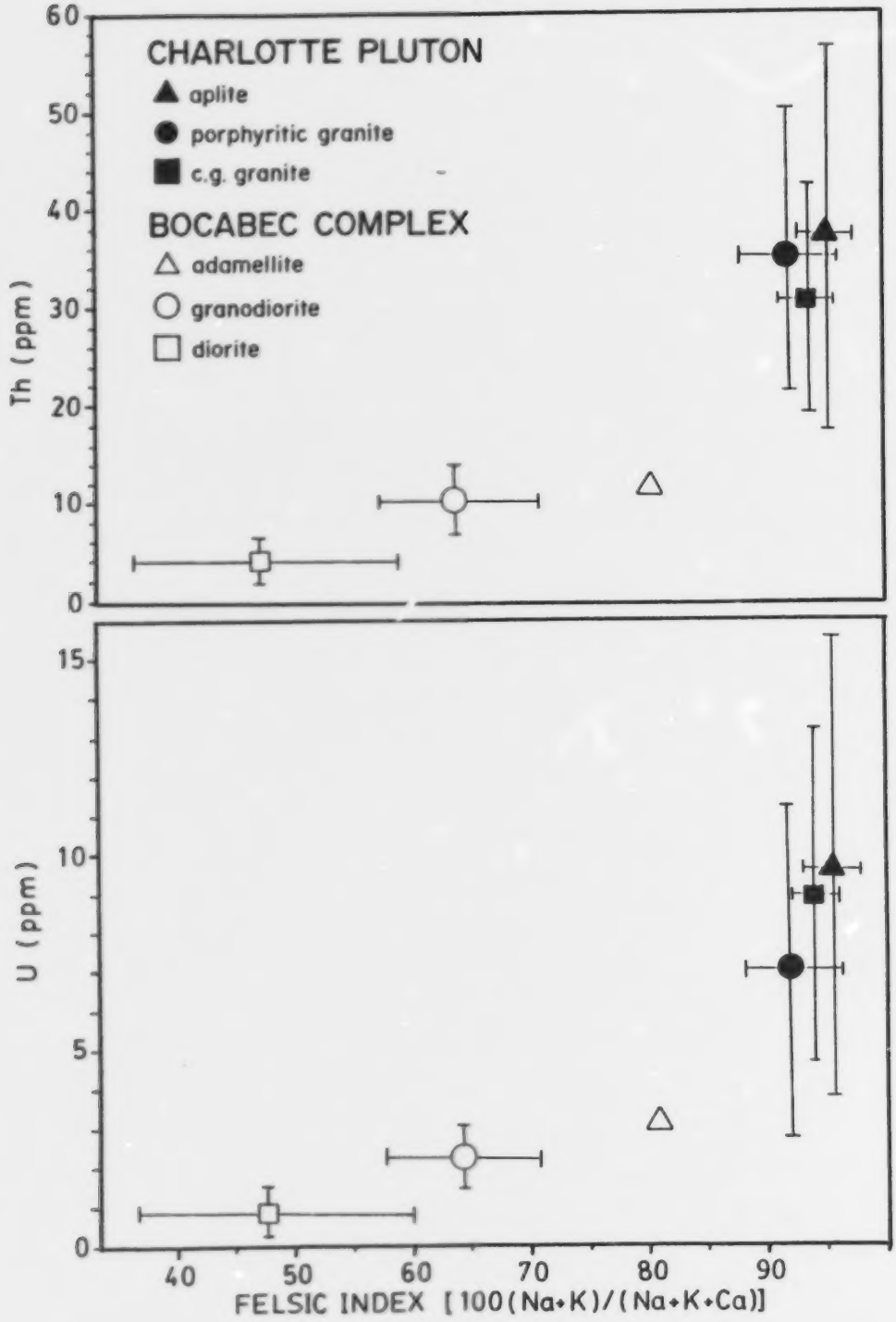


Figure 26. U and Th vs. felsic index for the St. George Batholith (bars are standard deviation of the mean).

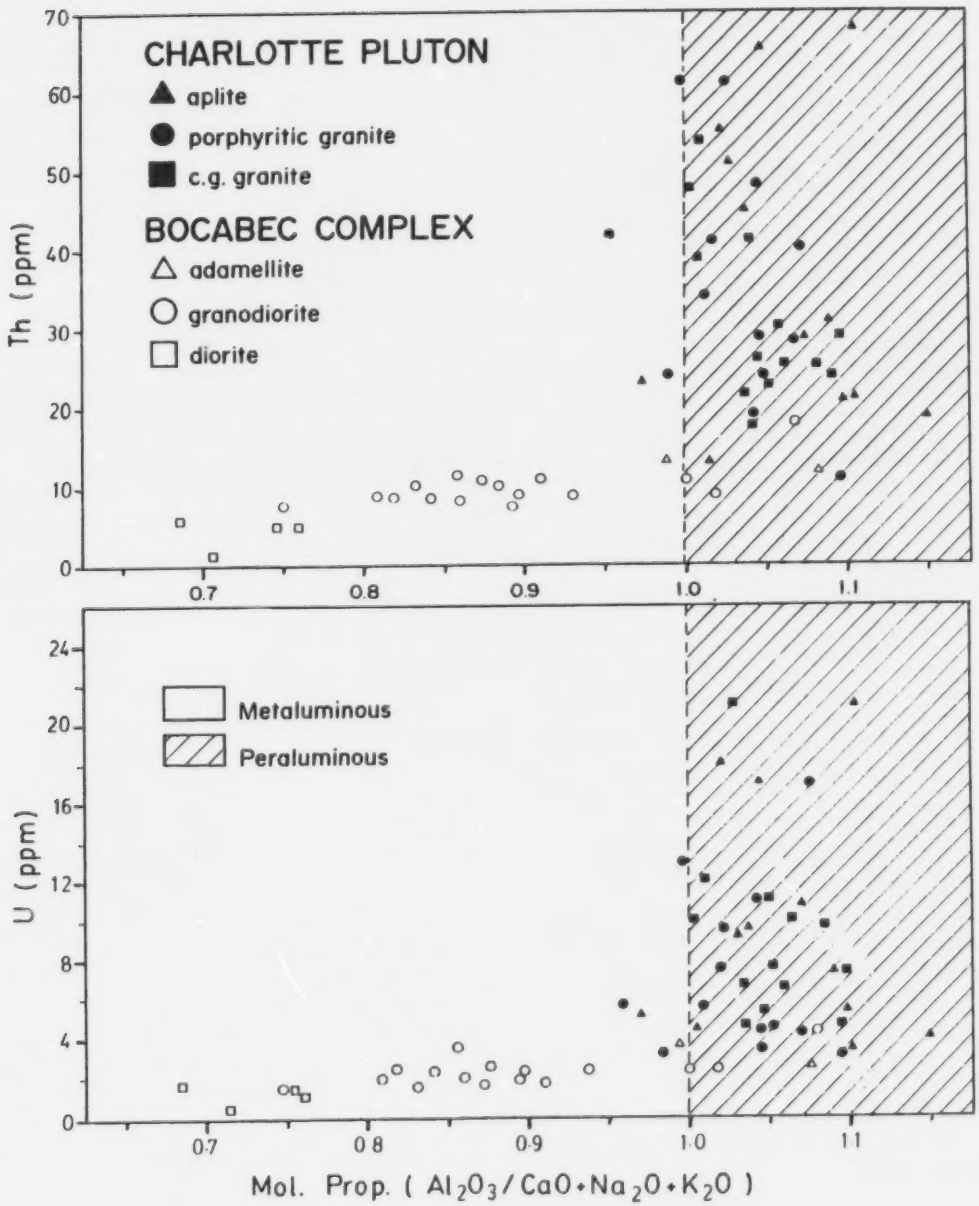


Figure 27. U and Th contents vs. degree of alumina saturation for rocks of the St.George Batholith (Charlotte Pluton and Bocabec Intrusive Complex).

those variations in U and Th contents that do exist appear to be related to the degree of magmatic differentiation. Furthermore, Figure 27 shows that the rocks of the Bocabec Intrusive Complex are mainly metaluminous and show a wide range of alumina-saturation index values but all contain little U and Th. The rocks of the Charlotte Pluton are mainly peraluminous and contain relatively higher U and Th content than the metaluminous rocks.

The plots of U and Th contents vs. the oxidation states for the rocks of the St. George Batholith (Figure 28) show poor positive correlations between these variables. This may suggest that both U and Th were only slightly mobilized by oxidation of the rocks in the St. George Batholith.

The correlation matrix of U, Th and the major oxides for all of the samples in the St. George Batholith rocks is shown in Figure 29. A significant positive correlation exists between U and both SiO_2 and K_2O, but a significant negative correlation exists between U and TiO_2; Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO and P_2O_5. Thorium follows the same pattern. No correlation is shown for either U or Th with Na_2O at the 90% confidence level. The nature of U and Th correlation with major oxides in the St. George Batholith is summarized in Figure 30.

The behaviour of U and Th in the last stages of magmatic differentiation of the St. George Batholith is represented by the rocks of the Charlotte Pluton (which have greater than 70 wt. % SiO_2). At this stage there is poor correlation between both U and Th and SiO_2 or K_2O (Figure 31). This suggests that both U and Th were partly redistributed in these rocks, perhaps by a postmagmatic process. Significant negative correlations exist for both U and Th, and TiO_2, Al_2O_3, Fe_2O_3 and P_2O_5. Among the trace elements, only Cu and Rb have a significant positive correlation with both U and Th. Stronium has significant negative correlation with U but not with Th. Chromium shows a poor negative correlation with both U and Th. No correlation exists for either U or Th and fluorine or zirconium. A summary of the correlations between U and Th and major, minor and trace elements in the granitic rocks of the Charlotte Pluton is displayed in Figure 32.

The average U and Th contents of rocks of the Charlotte Pluton are 8.59 ppm and 34.45 ppm, respectively. These values are about twice the average U and Th contents of granites (granites contain, on average, worldwide, 4.0 ppm U and 17.0 ppm Th). Therefore, the Charlotte Pluton can be considered 'uraniferous' according to Darnley's (1982) definition for uraniferous granites. Darnley suggested the term 'uraniferous' for those granites which contain U at least twice the Clarke value. In the same way, the Charlotte Pluton may also be considered as 'thoriferous' since its average Th content exceeds that of the 'average' granite by a factor of two.

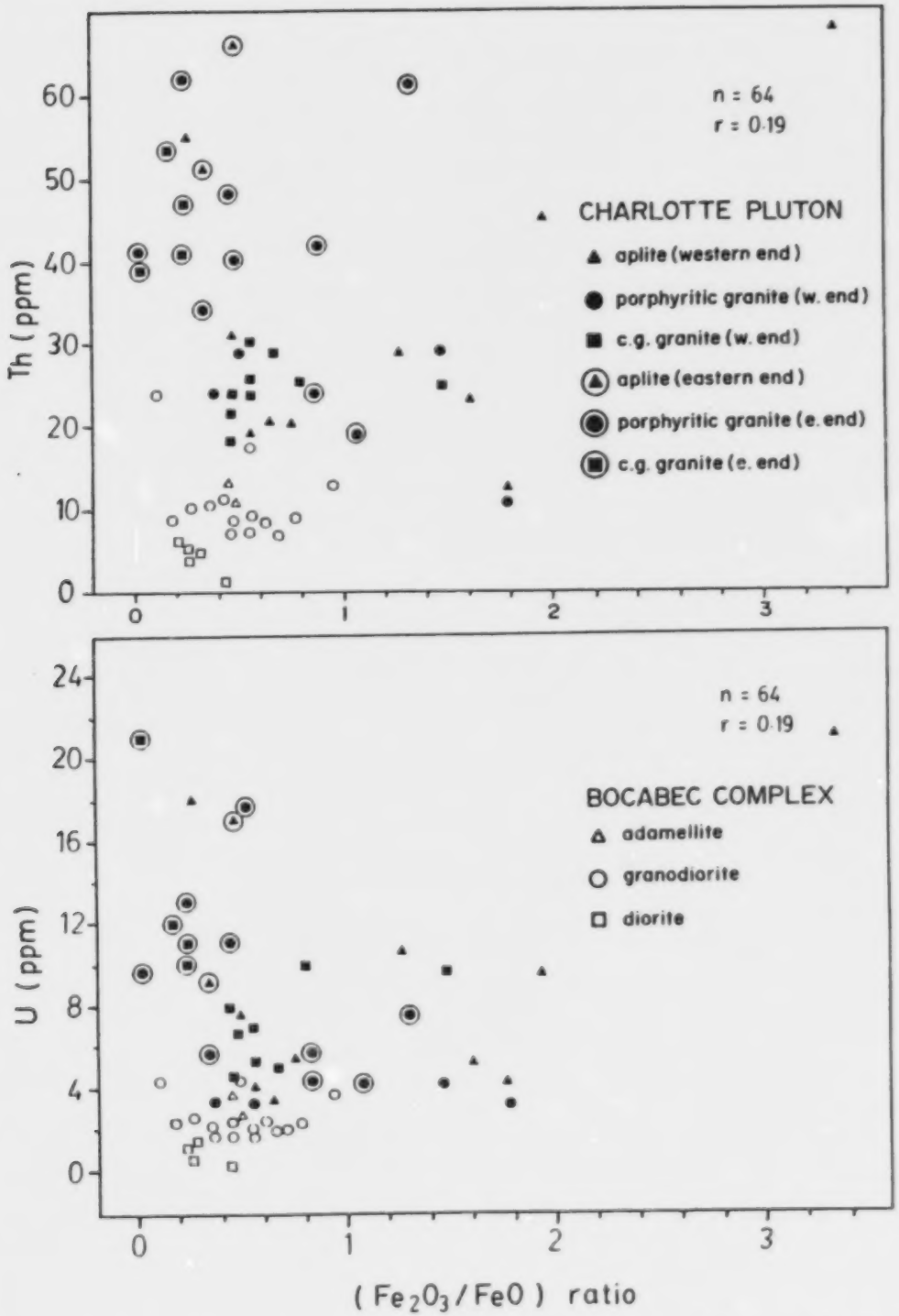


Figure 28. U and Th contents vs. oxidation state for rocks of the St. George Batholith.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	U	Th	Th/U
Th/U	-0.04	0.04	0.10	0.00	0.03	0.03	0.07	0.01	-0.09	0.01	-0.02	-0.35	0.09	1.00
Th	(0.73)	(-0.73)	(-0.69)	(-0.70)	(-0.72)	(-0.73)	(-0.59)	(-0.67)	-0.20	(0.68)	(-0.62)	(0.85)	1.00	
U	(0.65)	(-0.67)	(-0.64)	(-0.63)	(-0.64)	(-0.64)	(-0.54)	(-0.60)	-0.16	(0.59)	-0.56	1.00		
P_2O_5	-0.72	0.85	0.62	0.81	0.80	0.79	0.47	0.63	0.54	-0.74	1.00			
K_2O	0.94	-0.91	-0.85	-0.77	-0.92	-0.86	-0.83	-0.90	-0.41	1.00				
Na_2O	-0.23	0.32	0.34	0.41	0.26	0.32	-0.08	0.14	1.00					
CaO	-0.94	0.86	0.86	0.72	0.87	0.75	0.92	1.00						
MgO	-0.90	0.78	0.76	0.58	0.83	0.70	1.00							
MnO	-0.88	0.95	0.65	0.83	0.95	1.00								
FeO	-0.96	0.97	0.75	0.78	1.00									
Fe_2O_3	-0.79	0.86	0.67	1.00										
Al_2O_3	-0.86	0.75	1.00											
TiO_2	-0.94	1.00												
SiO_2	1.00													

Figure 29. Correlation matrix for 54 samples of the St. George Batholith. Values in brackets indicate significant correlations with U and Th at the 95% confidence level.

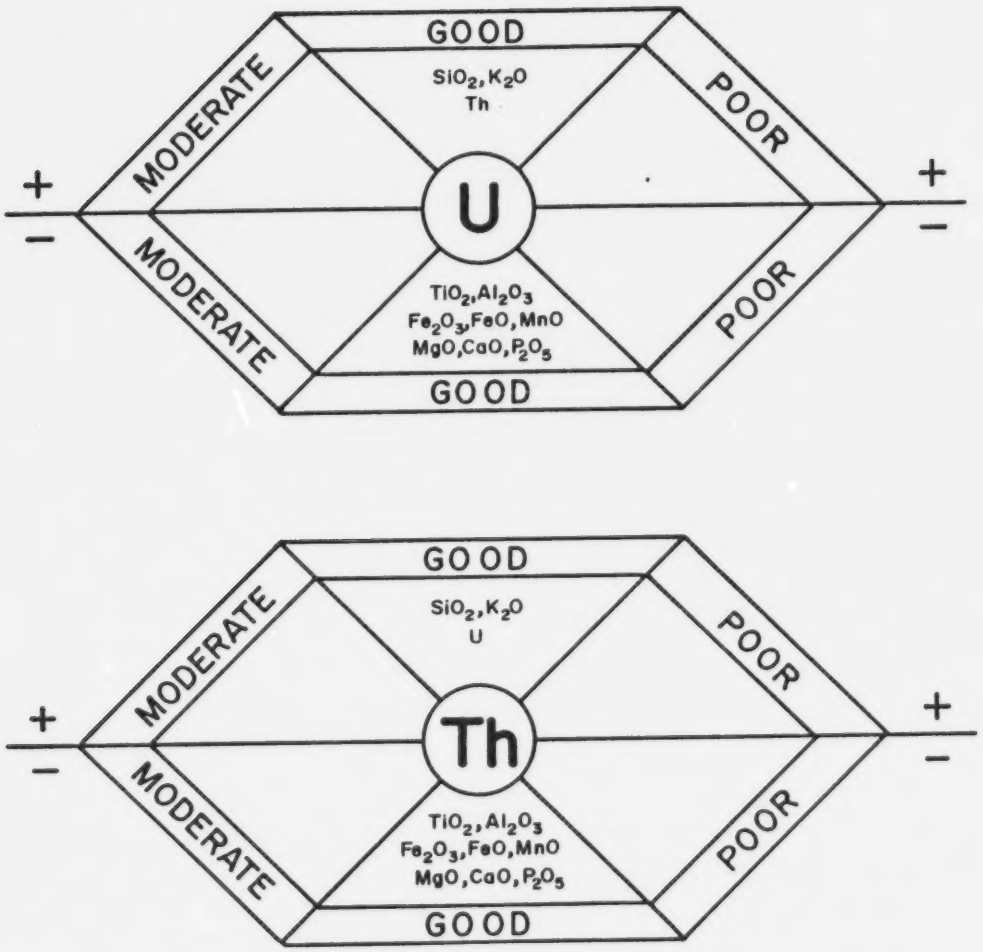
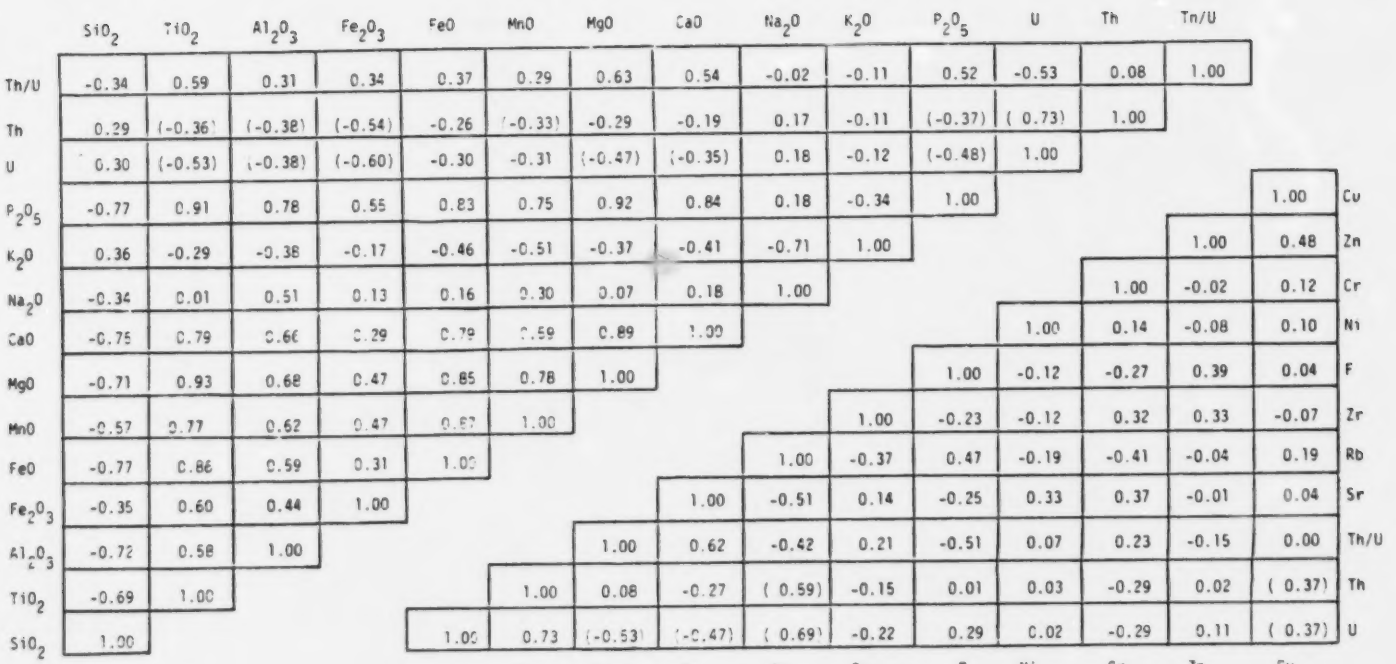


Figure 30. Summary diagram of the degree of correlation between U and Th and major elements in the St. George Batholith.



	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	U	Th	Th/U	
Th/U	-0.34	0.59	0.31	0.34	0.37	0.29	0.63	0.54	-0.02	-0.11	0.52	-0.53	0.08	1.00	
Th	0.29	(-0.36)	(-0.38)	(-0.54)	-0.26	(-0.33)	-0.29	-0.19	0.17	-0.11	(-0.37)	(0.73)	1.00		
U	0.30	(-0.53)	(-0.38)	(-0.60)	-0.30	-0.31	(-0.47)	(-0.35)	0.18	-0.12	(-0.48)	1.00			
P_2O_5	-0.77	0.91	0.78	0.55	0.83	0.75	0.92	0.84	0.18	-0.34	1.00				1.00 Cu
K_2O	0.36	-0.29	-0.38	-0.17	-0.46	-0.51	-0.37	-0.41	-0.71	1.00				1.00	0.48 Zn
Na_2O	-0.34	0.01	0.51	0.13	0.16	0.30	0.07	0.18	1.00				1.00	-0.02	0.12 Cr
CaO	-0.75	0.79	0.66	0.29	0.79	0.59	0.89	1.00				1.00	0.14	-0.08	0.10 Ni
MgO	-0.71	0.93	0.68	0.47	0.85	0.78	1.00				1.00	-0.12	-0.27	0.39	0.04 F
MnO	-0.57	0.77	0.62	0.47	0.67	1.00				1.00	-0.23	-0.12	0.32	0.33	-0.07 Zr
FeO	-0.77	0.86	0.59	0.31	1.00				1.00	-0.37	0.47	-0.19	-0.41	-0.04	0.19 Rb
Fe_2O_3	-0.35	0.60	0.44	1.00				1.00	-0.51	0.14	-0.25	0.33	0.37	-0.01	0.04 Sr
Al_2O_3	-0.72	0.58	1.00				1.00	0.62	-0.42	0.21	-0.51	0.07	0.23	-0.15	0.00 Th/U
TiO_2	-0.69	1.00				1.00	0.08	-0.27	(0.59)	-0.15	0.01	0.03	-0.29	0.02	(0.37) Th
SiO_2	1.00				1.00	0.73	(-0.53)	(-0.47)	(0.69)	-0.22	0.29	0.02	-0.29	0.11	(0.37) U
					U	Th	Th/U	Sr	Rb	Zr	F	Ni	Cr	Zn	Cu

Figure 31. Correlation matrix for 38 samples from the Charlotte Pluton. Values in brackets indicate significant correlations with U and Th at the 95% confidence level.

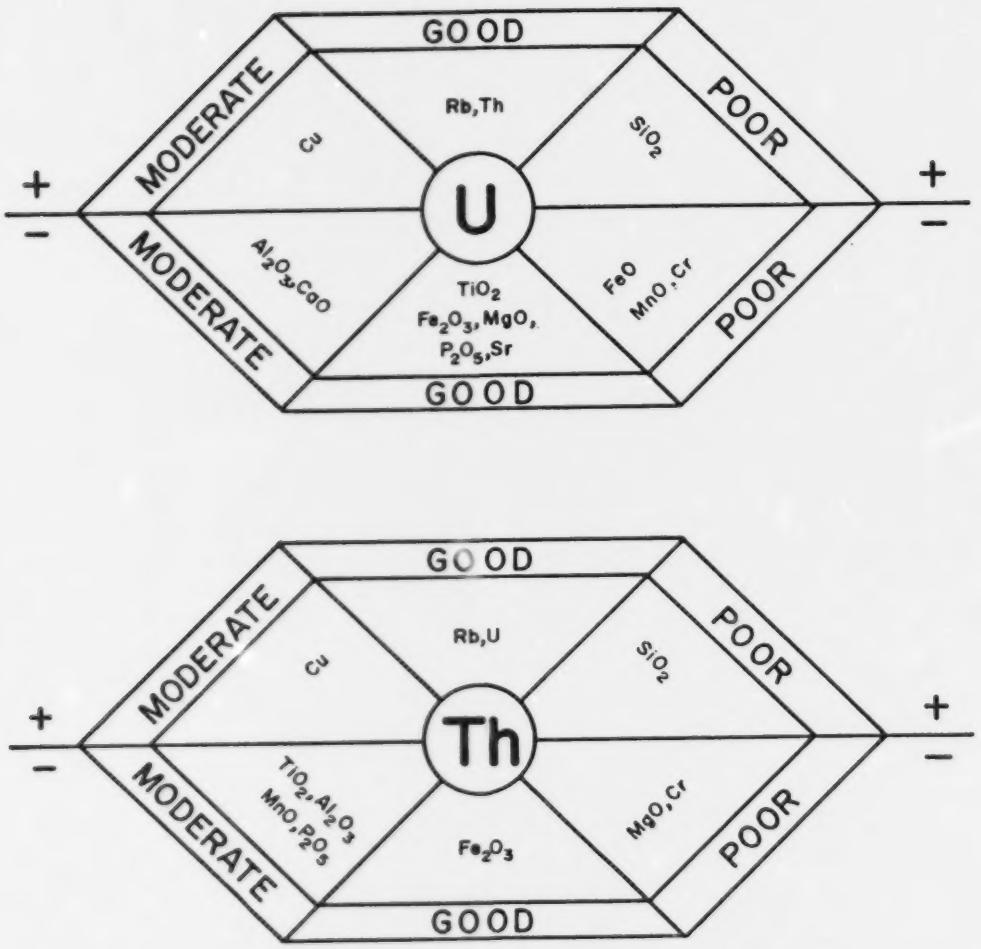


Figure 32. Summary diagram of the degree of correlation between U and Th and major, minor and trace elements in the granitic rocks of the Charlotte Pluton of the St. George Batholith.

Most of the uraniferous and thoriferous rock samples are located in the eastern end of the Charlotte Pluton. The average U and Th contents are 10.6 ppm and 44.5 ppm, respectively, in the eastern end of the pluton whereas they are 7.3 ppm and 27.9 ppm, respectively, in its western end. These variations are consistent with the major, minor and trace element trends between the eastern and western end of the Charlotte Pluton (Table 3). The chemical and textural data suggest that the eastern end of the Charlotte Pluton contains the most differentiated rocks (Cherry, 1976) and is the place where the apex of magmatic evolution was reached. The residual magma was highly enriched in U, Th, alkalies, silica and volatiles. The presence of pegmatitic pods in the eastern end of the pluton, and their absence in its western end, suggest the existence of a separate fluid phase in the eastern end.

Cherry (1976) has attributed the abundance of pegmatitic pods, miarolitic cavities, rapakivi mantles, granophyric intergrowths, and the porphyritic granites to a decrease in pressure and then separation of a volatile-rich phase from the magma. The pegmatitic pods are generally less than 50 cm in diameter. Seven in situ gamma-ray spectrometry readings were carried out over these pegmatitic pods; they yield an average U and Th content of about 12.94 ppm and 47.23 ppm, respectively. Because of the small size of these pods and hence the small area of influence on the spectrometer sensor, these averages are certainly much less than the actual U and Th contents in these pods.

Whole-rock chemical compositions and other geological and geophysical aspects of the Charlotte Pluton are compared with similar aspects of 'normal' granites and the 'uraniferous' Cairgorm granite of the British Caledonian (Table 4). This comparison suggests that the Charlotte Pluton is similar to other uraniferous granites and is characterized by high SiO_2, Na_2O, K_2O, Rb, Ni, U and Th and low Al_2O_3, FeO , MgO, CaO, P_2O_5, Sr and Zr relative to the 'average' granite. The low F content of the Charlotte Pluton relative to the 'average' granite may be attributed to the release of an aqueous, F-bearing phase during late stages of the Charlotte Pluton's evolution.

The presence of pitchblende-uraninite-bearing veins along fractures in the eastern end of the pluton, at Eagle Rock Cliff (Welsford, Map Plate 86-213), suggests that hydrothermal solutions may have been generated during the final stages of magmatic differentiation. Uraninite and thorite are the only radioactive minerals to have been identified in these veins.

Variation of U and Th Contents With Depth in the Charlotte Pluton

Maps based on airborne gamma-ray spectrometry for U and Th (G.S.C. Geophysical Series, Map 35721G) over the Charlotte

Table 3.
Range, Mean and Standard Deviations of Abundances of Major, Minor and Trace Elements, Western and Eastern Charlotte Pluton.

OXIDES AND ELEMENTS	WESTERN END			EASTERN END		
	n	range	mean	n	range	mean
SiO_2 (%)	23	69.0-78.4	75.1±2 2	15	73 3-78.8	76.5±1.4
TiO_2 (%)	23	0.06-0.62	0.20±0.13	15	0.11-0.31	0.17-0.06
Al_2O_3 (%)	23	12.1-14.4	13.0±0.6	15	11.8-13.4	12.3±0.4
Fe_2O_3 (%)	23	0.20-1.23	0.67±0.30	15	0.02-0.70	0.32±0.18
FeO (%)	23	0.18-2.39	0.93±0.56	15	0.3-1.5	0.85±0.30
MnO (%)	20	0.01-0.09	0.03±0.02	13	0.01-0.05	0.02±0.01
MgO (%)	23	0.02-0.86	0.20±0.22	15	0.06-0.56	0.16±0.13
CaO (%)	23	0.12-2.08	0.61±0.46	15	0.3-1.45	0.6±0.3
Na_2O (%)	23	2.9-4.3	3.5±0.3	15	2.8-3.6	3.3±0.2
K_2O (%)	23	3.8-5.9	4.8±0.58	15	4.6-5.6	5.13±0.25
P_2O_5 (%)	23	0.03-0.16	0.05±0.03	15	0.03-0.07	0.04±0.01
Sr (ppm)	17	2.00-143.0	45.8±43.7	15	6.0-137.0	30.3±34.6
Rb (ppm)	23	150.0-466.0	283.3±85.0	15	216.0-445.0	357.1±70.1
Zr (ppm)	23	47.0-622.0	155.8±114.8	15	91.0-191.0	124.3±24.8
F (ppm)	8	70.00-1500.0	667.5±537.4	8	80.0-1400.0	516.2±424.9
Ni (ppm)	22	2.20-32.0	12.4±8.1	15	2.4-26.8	13.8±7.2
Cr (ppm	21	1.50-15.0	6.6±3.5	15	3.0-14.5	5.8±3.4
Zn (ppm)	22	13.0-144.0	47.1±33.1	15	14.5-209.0	38.8±47.8
Cu (ppm)	21	2.0-8.0	4.6±1.4	15	2.50-13.5	5.7±3.0
U (ppm	23	3.10-21.00	7.3±4.5	15	4.3-21.0	10.6±4.9
Th (ppm)	23	11.00-68.00	27.9±12.7	15	19.0-66.0	44.5±13.2
Th/U ratio	23	2.50-8.5	4.3±1.6	15	1.9-8.0	4.7±1.6

Table 4.
Comparison of Whole-rock Chemistry, and Geological and Geophysical Characteristics of the Charlotte Pluton With Uraniferous Granitoid of the British Caledonian and an 'Average' Granite.

	CATEGORIES	(a) AVERAGE GRANITE	URANIFEROUS GRANITE (British Caledonian-Cairngorm) n=69 (b)	CHARLOTTE PLUTON (SW. New Brunswick) n=37 (c)
WHOLE - ROCK CHEMISTRY	SiO_2 (%)	71.30	-----	75.70±2.05
	TiO_2 (%)	0.31	0.13±0.69	0.19±0.11
	Al_2O_3 (%)	14.32	-----	12.74±0.66
	Fe_2O_3 (%)	1.21	0.88±0.29	0.53±0.31
	FeO (%)	1.64	-----	0.90±0.47
	MnO (%)	0.05	-----	0.03±0.02
	MgO (%)	0.71	0.13±0.82	0.18±0.19
	CaO (%)	1.84	0.26±0.15	0.59±0.40
	Na_2O (%)	1.68	3.13±0.37	3.49±0.32
	K_2O (%)	4.07	5.00±0.83	4.94±0.50
	P_2O_5 (%)	0.12	-----	0.05±0.03
	Sr (ppm)	285.00	67.00±27.00	38.53±39.87
	Rb (ppm)	150.00	455.00±96.00	312.42±86.56
	Zr (ppm)	180.00	65.00±48.00	143.37±91.20
	Ni (ppm)	0.50	4.90±11.00	12.99±7.69
	Zn (ppm)	40.00	28.00±14.90	43.76±39.30
	Cu (ppm)	10.00	0.00	5.06±2.25
	Cr (ppm)	4.00	6.20±4.2	6.11±3.47
	F (ppm)	810.00	-----	582.35±461.13
	Pb (ppm)	20.00	26.00±9.9	-----
	Co (ppm)	1.00	1.20±7.3	-----
	Li (ppm)	30.00	75.00±31.0	-----
	Ba (ppm)	600.00	258.00±145.0	-----
	U (ppm)	4.00	12.60±5.6	8.59±4.89
	Th (ppm)	17.00	26.80±9.1	34.45±15.17
GEOCHEMICAL ALTERATIONS			Two-mica granite(muscovite replacing biotite. Sericitization and kaolinitzation of feldspars. Chloritization, hematitization and epidotization of ferromagnesian minerals. Tourmalinization. Greisenization.	Chloritization. Sericitization. Hematitization. Greisenization.
ACCESSORY MINERALS			Uraninite,thorite,uranothorite, fluorite,topaz,beryl,cassiterite, columbite-tantalite,xenotime, monazite,apatite.	Uraninite,thorite,fluorite, apatite,muscovite,sphene, zircon.
AGE			Late Silurian/Lower Devonian	Mid-Devonian
MAGMA GENERATION			Partial melting of lower Crust/ Upper Mantle	Anatectic melt of sialic crust
MAGMA TYPE			Calc-alkaline to alkaline	Calc-alkaline
LEVEL OF EMPLACEMENT			High level (Epizonal)	High level (Epizonal)
TECTONIC STAGE			Post-orogenic	Post-orogenic
GEOPHYSICAL CHARACTERISTICS			-Strong negative Bouguer gravity anomaly(≃-40 mgls) -Strong,broad large-amplitude magnetic anomalies. -High heat flow	-Strong negative Bouguer gravity anomaly(∼-40 mgls) -High heat flow

n = number of samples
± error above the mean expressed by the standard deviation.

(a) average major element compositions from LeMaitre(1976);Sr,Rb,Zr,Ni,Zn,Cu,Cr,U,Th,Pb, Co,Li and Ba from Taylor(1964);F from Allmann and Koritnig(1969).

(b) gravity and heat flow data from Darnley(1982);other data from Simpson et al.(1979) and Plant et al.(1980).

(c) gravity data from Wallace et al.(1979);heat flow data from Chandra(per. comm.,1981); other data from Cherry(1976).

Pluton (Figure 33) and the in situ gamma-ray spectrometry data collected in the present study reveal spatial variations in both U and Th over the pluton. Similar variations, are also observed in chemical, petrological and textural data by Cherry (1976). The eastern end of the pluton has higher U and Th contents than its western end. Whether this variation is only surficial or extends to depth in these rocks was not known before the present study.

To determine if there is any variation of U and Th content with depth in the granitic rocks of the Charlotte Pluton, two drill cores, one in the eastern end of the pluton, near Trout Lake (T2 on Map Plate 86-213), and the other at its western end, at Lily Lake (L1), were investigated. These cores were sampled at an interval of 1 m and sent for U and Th analysis by neutron activation at X-ray Laboratories, Ltd., Ontario.

The drill cores (T2) from the Trout Lake borehole were sampled to a depth of about 102 m below the surface. The U and Th contents for the surface granite at the top of this hole as determined by gamma-ray spectrometry are 7.0 ppm and 29.0 ppm, respectively. The mean U and Th contents for the total samples assayed from this borehole are 11.5 ppm and 31.4 ppm, respectively. This suggests that the U and, to some extent, Th content increase with depth or that they were depleted from the near-surface rocks. It is believed that some geological process such as weathering has preferentially removed the U and, to a lesser extent, Th in the near-surface environment. The average Th/U ratio in the deeper rocks in this borehole is about 2.8, which is below the average worldwide Th/U ratio of 4.0 for granites. This suggests a preferential enrichment of U relative to Th at depth in the eastern end of the Charlotte Pluton.

The plot of U, Th and Th/U ratio variations with depth, as well as the core profile for the Trout Lake borehole is shown in Figure 34. Variations in U and Th in these cores are related to microfractures, joints, and hematitic stains.

To remove minor variations caused by the above effects and define the generalized trends of U, Th and the Th/U ratio with depth, cubic (third order) best-fit regression lines were constructed for the original data (Figure 35). These regression lines indicate that both U and Th are depleted in the top 30 m of the rocks. It appears also from these profiles that while Th content tends to be constant below about 70 m, U increases slightly. The Th/U ratio increases toward the top of these rocks, apparently as a result of the preferential leaching of U relative to Th in the near-surface rocks. The lake and stream sediments in the vicinity of the borehole contain from 8.2 ppm to 23.2 ppm U (Austria, 1977) relative to the background which is equal to 6.8 ppm U. This also suggests that U is being leached from the surface rocks.

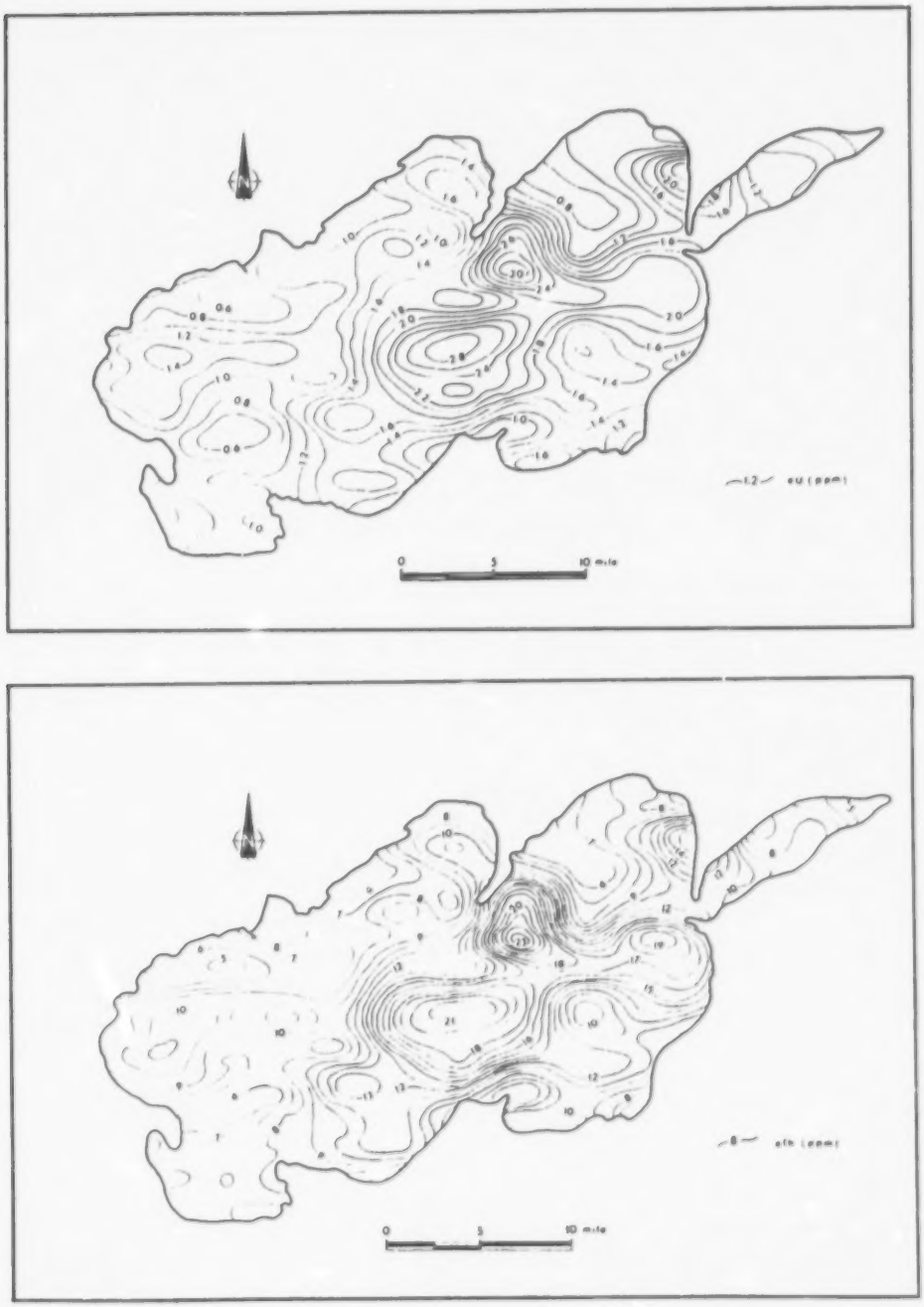


Figure 33. Airborne radiometric contours of equivalent-uranium and equivalent-thorium over the granitic rocks of the Charlotte Pluton of the St. George Batholith.

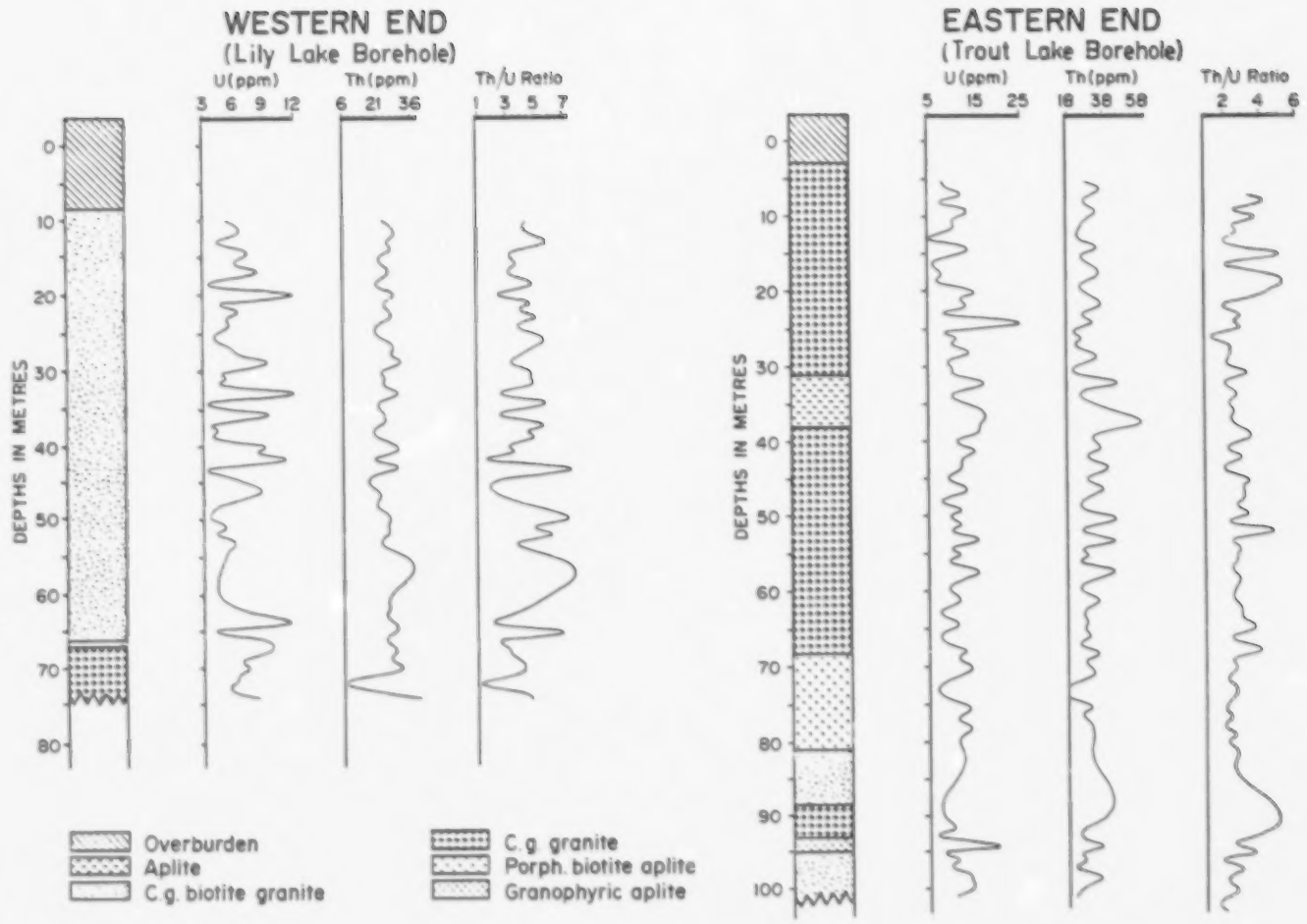


Figure 34. Variation in U, Th, and Th/U ratio below the ground surface of the granitic rocks at the eastern and western ends of the Charlotte Pluton of the St. George Batholith.

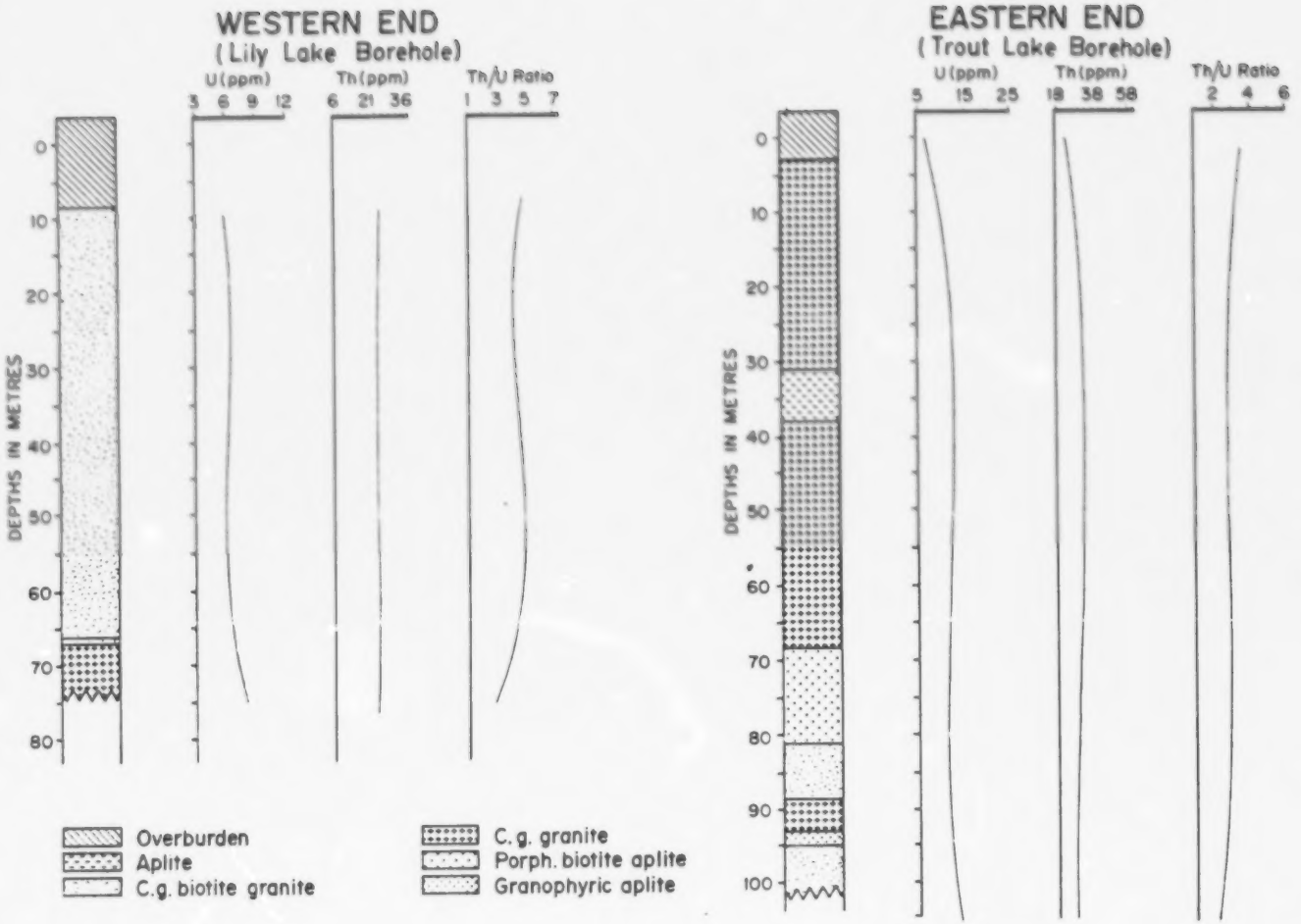


Figure 35. Third-order best fit regression lines constructed for U, Th, and Th/U ratio below the ground surface of the granitic rocks at the eastern and western ends of the Charlotte Pluton of the St. George Batholith.

The western-end borehole is located about 1.5 km east of Lily Lake. Cores were obtained to about 75 m below the ground surface. The in situ gamma-ray spectrometry for the surface granite at this hole registered 3.4 ppm U and 22.5 ppm Th. The mean U and Th contents for the total samples assayed in this borehole are 6.3 ppm and 24.7 ppm, respectively; thus they exceed the contents of the surface rocks. The average Th/U ratio in the subsurface rocks is about 4.3, which is close to the worldwide average Th/U ratio for granites.

The variations of U, Th and Th/U ratio with depth, as well as the core profile for the Lily Lake borehole are shown in Figure 34. Uranium displays great variability compared to Th. Detailed inspection of the core samples reveals that most of the rocks are altered. This alteration has led to the release of uranium and its redistribution throughout the drilled part of the Charlotte Pluton. Most of the U released was reprecipitated along small quartz veins (most U peaks observed on the profile are associated with quartz veins). It appears that Th has not been affected by the alteration processes.

The third order best-fit regression lines for the original data are displayed in Figure 35 and clearly indicate that U increases in abundance with depth, whereas Th tends to be constant in abundance with depth. The Th/U ratio accordingly decreases with depth. The release of U from the surface rocks and its distribution in weathered products is also supported by lake and stream sediment samples in the vicinity of this borehole in which U ranges from 2.8 ppm to 122.0 ppm (Austria, 1977).

Factor Analysis of the Geochemical Data

Factor analysis is used in an attempt to recognize groups of associated elements which would permit an interpretation of the elemental associations in terms of geological processes.

The general aim of factor analysis is to find the minimum number of variables that are necessary to account for the maximum observed variation in the data, to identify these controlling variables and to determine the relative contribution of individual variables in terms of the controlling variables (CEGS, 1968). Factor analysis is used to find associations and antipathies between groups of elements or to recognize similar behaviour of different elements and to interpret these associations in terms of geological phenomena. Since we are interested in the behaviour of U and Th with other elements in selected igneous rocks, R-mode factor analysis was carried out using the (BMD-P4M) program provided in the Biomedical statistical package of Health Sciences Computing Facility of University of California, Los Angeles (revised Nov. 1979).

St. George Batholith: Results of a factor analysis of the rocks of the St. George Batholith are presented in Table 5 and reveal that the squared multiple correlations (SMC) of each oxide or element with all other oxides or elements are high, indicating a high degree of common variance among the variables. The communalities (sum of the squared factor loadings for each variable) are also high except for those of U and Th which are moderately high (A communality is a measure of the proportion of a variable sharing something in common with other variables in the data). Eigenvalues and the corresponding percentages of explained variation in each of the factors are also given in Table 5.

As can be seen from Table 6, the first factor accounts for 76% of the variations, the second for 12.5%, and the third for 11.5%. The three factors and their loadings obtained after VARIMAX rotation are also given in Table 6. The VARIMAX rotation is applied to maximize the discriminability of the factors. This is done by moving the factor axis to successive positions such that the loadings of each variable onto the factor axes are either near the extremities or near the origin (i.e., approaches either ± 1 or zero). This is illustrated on Figure 36, plots of factor I and factor II plane for the original and the VARIMAX rotated data; on these plots the relationship between variables is expressed by the angle between two vectors (the smaller the angle the higher the relationship), whereas the magnitude of the variable is given by the vector length.

Table 6 and Figure 36 indicate that the first factor shows a predictable antipathetic relationship between the so called "mafic" oxides (Fe_2O_3, FeO, MnO, MgO and CaO) and SiO_2 and K_2O; U and Th join SiO_2 and K_2O in this factor. This suggests that both U and Th variations in the St. George Batholith are mainly controlled by its crystallization history and probably by magma-crystal equilibrium, possibly during magmatic differentiation.

The second factor, which explains less than 13% of the variation in the batholith, separate K_2O, U and Th from all the other oxides; this portion may be related to the partitioning of U, Th and K from the main granitic rocks of the St. George Batholith and their enrichment in the fluid phases separated from the magma at its latest stages of differentiation.

Charlotte Pluton: Factor analyses of the abundances of major and trace elements were carried out for the Charlotte Pluton, which is representative of the latest stages of the St. George Batholith's evolution. Uranium and Th were compared first with the major elements and then with the minor and trace elements of the Charlotte Pluton.

TABLE 5.

Left Side: Square Multiple Correlation (SMC) and Communalities of the Variables;
Right Side: Eigenvalues and Percent of Variances Accounted for each of the Factors for U, Th, and Major Element Contents of the St. George Batholith.

Oxides and Elements	SMC	Communalities (h^2)
SiO_2	0.96	0.97
TiO_2	0.98	0.95
Al_2O_3	0.91	0.91
Fe_2O_3	0.89	0.83
FeO	0.99	0.84
MnO	0.96	0.87
MgO	0.94	0.91
CaO	0.95	0.89
Na_2O	0.82	0.89
K_2O	0.96	0.89
P_2O_5	0.87	0.87
U	0.75	0.57
Th	0.79	0.67

Factors	Eigenvalues	Percent Variance	Cumulative Percent
I	8.49	65.3	65.30
II	1.39	10.69	75.99
III	1.28	9.85	85.84
IV	0.79	6.08	91.92
V	0.42	3.23	95.15
VI	0.20	1.54	96.69
VII	0.16	1.23	97.92
VIII	0.14	1.08	99.00
IX	0.05	0.38	99.38
X	0.04	0.31	99.69
XI	0.03	0.23	99.92
XII	0.02	0.15	100.0
XIII	0.01	0.08	100.0

Table. 6
Original and VARIMAX-rotated Factor Loadings
for the First Three Factors Retained for U, Th and
Major Elements of the St. George Batholith.

Factors / Variables	Unrotated Factor Loadings			Rotated Factor Loadings		
	F I	F II	F III	F I	F II	F III
SiO_2	-0.67	0.72	0.02	-0.85	0.45	-0.23
TiO_2	0.96	0.15	0.02	0.80	0.47	0.31
Al_2O_3	0.49	0.81	-0.12	0.19	0.93	-0.01
Fe_2O_3	0.86	0.21	0.20	0.63	0.48	0.44
FeO	0.96	-0.08	-0.05	0.90	0.26	0.25
MnO	0.92	0.14	0.06	0.75	0.44	0.33
MgO	0.82	-0.05	-0.48	0.90	0.26	-0.19
CaO	0.90	-0.08	-0.26	0.91	0.25	0.04
Na_2O	0.33	-0.13	-0.87	0.06	-0.06	0.94
K_2O	-0.94	0.11	-0.02	-0.86	-0.21	-0.32
P_2O_5	0.82	0.21	0.38	0.54	0.46	0.60
U	-0.74	0.12	0.08	-0.72	-0.14	-0.16
Th	-0.80	0.14	0.06	-0.78	-0.14	-0.20
Variance Explained By Factor	8.49	1.39	1.28	6.96	2.22	1.97
Percent Explained	76.00	12.50	11.50	62.40	19.90	17.70

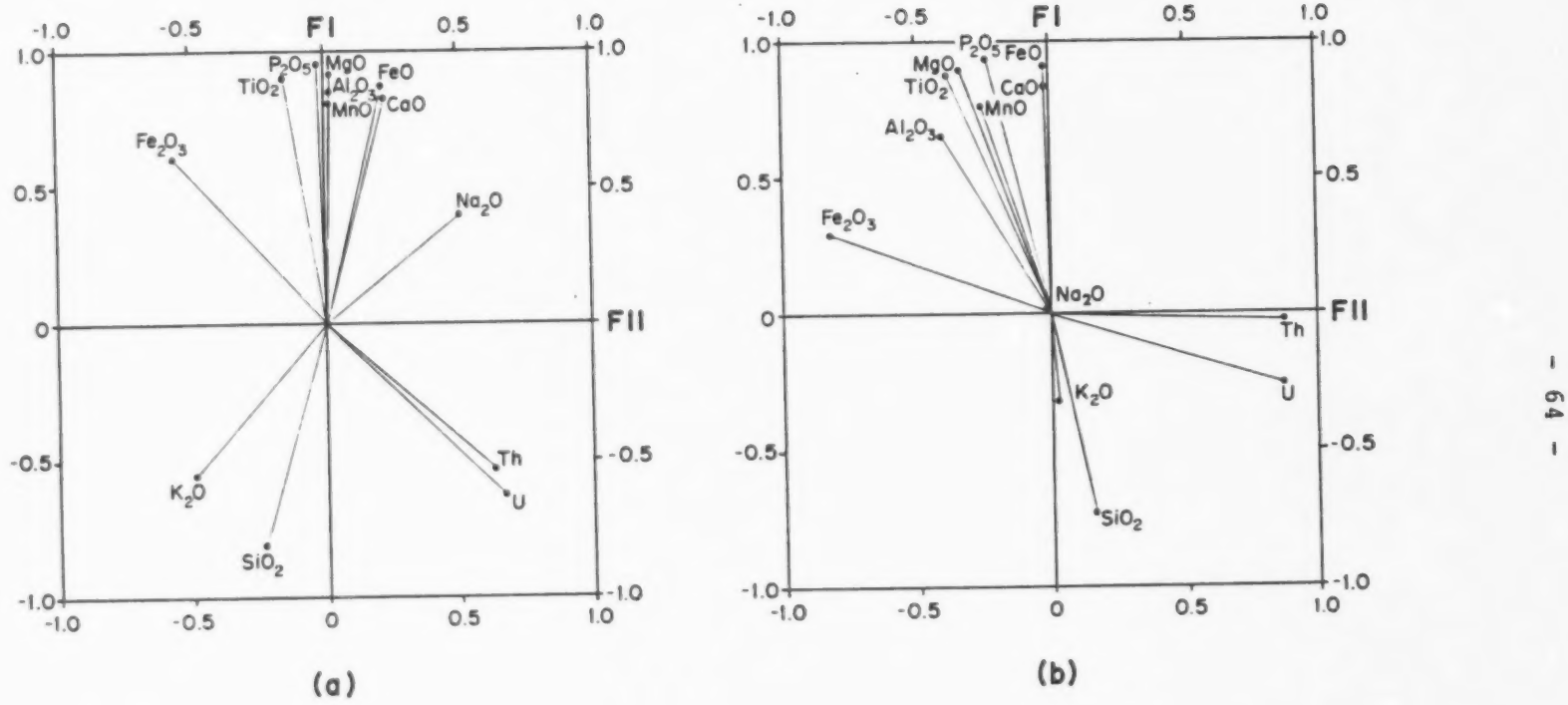


Figure 36. Plots of loadings on the first two factors extracted from U, Th, and major element contents of the St. George Batholith; (a) original loading, (b) after VARIMAX rotation.

The square multiple correlations and the communalities of the major elements are fairly high (Table 7). The first factor (Table 8), which accounts for nearly 70% of the variation, contains most of the major elements and separates SiO_2, K_2O, U and Th from the rest of the major elements. This factor is related to degree of magmatic differentiation.

The second factor separates TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO and P_2O_5 from SiO_2, K_2O, U and Th. The factor loadings of SiO_2 and K_2O are very low on this factor. Therefore, the high contribution of U and Th on this factor may suggest that some U and Th were probably depleted from the granitic rocks and redistributed within the Charlotte Pluton to form secondary accumulations of U and Th. These secondary accumulations of U and Th have no significant relationship to the abundance of the major elements. The third factor contains no significant U and Th. The plots of the first two factors (Figure 37) indicate the high dispersion of the variables, particularly between U, Th, SiO_2 and K_2O. The dispersion and lack of correlation between these variables is believed to be due to hydrothermal alteration and U-Th mineralization at late stages of magmatic evolution.

Factor analysis of the relationship between U and Th and minor and trace elements in the Charlotte Pluton identified three factors with eigenvalues greater than unity (Table 9); these account for nearly 81% of the total variation and are further described by Table 10 and Figure 38. The first factor, which accounts for nearly 65% of the variation, separates the minor and trace elements into two groups: Sr, Zr, Ni, Cr and Zn on the one hand, and Rb, Cu, Th and U on the other hand (Table 10). Although F is associated with U and Th in this factor its contribution is minor. The second factor includes minor Ni, which is antipathetic to Cr, Cu, and U; other elements make only small contributions. This factor is interpreted as resulting from mineralization of these rocks in which U is associated with Cr and Cu but not with Ni or even with Th. U and Th have only a very minor influence on the third factor, which is overwhelmingly a function of F content.

GRANITIC STOCKS

The average abundances of major, minor and trace elements, including U and Th, in the rocks of southwestern New Brunswick granitic stocks are given in Table 11. The Beech Hill and the Sorrel Ridge stocks are the youngest; the Musquash stock is the oldest. The Musquash and Mohannas stocks are pre-orogenic (pre-Acadian) instrusions, whereas the Beech Hill, Sorrel Ridge, Tower Hill and Pleasant Ridge stocks and the South Oromocto Dyke are post-orogenic (post-Acadian) intrusions (Butt, 1976).

TABLE 7.

Left Side: Square Multiple Correlation (SMC) and Communalities of the Variables;
Right Side: Eigenvalues and Percent of Variances Accounted for each of the Factors for U, Th, and Major Element Contents of the Charlotte Pluton.

Oxides and Elements	SMC	Communalities (h^2)
SiO_2	0.77	0.74
TiO_2	0.97	0.95
Al_2O_3	0.93	0.80
Fe_2O_3	0.76	0.77
FeO	0.94	0.90
MnO	0.89	0.69
MgO	0.98	0.96
CaO	0.94	0.81
Na_2O	0.89	0.92
K_2O	0.80	0.79
P_2O_3	0.96	0.95
U	0.79	0.82
Th	0.78	0.81

Factors	Eigenvalues	Percent Variance	Cumulative Percent
I	7.62	58.62	58.62
II	1.90	14.62	73.24
III	1.39	10.69	83.93
IV	0.63	4.85	88.78
V	0.43	3.31	92.09
VI	0.35	2.69	94.78
VII	0.23	1.77	96.55
VIII	0.21	1.62	98.17
IX	0.10	0.77	98.94
X	0.08	0.62	99.56
XI	0.04	0.31	99.87
XII	0.02	0.15	100.00
XIII	0.01	0.08	100.00

Table 8.
Original and VARIMAX-rotated Factor Loadings
for the First Three Factors Retained for U, Th and
Major Elements of the Charlotte Pluton.

Factors / Variables	Unrotated Factor Loadings			Rotated Factor Loadings		
	F I	F II	F III	F I	F II	F III
SiO_2	-0.82	-0.26	-0.01	-0.74	0.13	-0.41
TiO_2	0.91	-0.17	-0.31	0.89	-0.39	-0.04
Al_2O_3	0.87	0.05	0.21	0.65	-0.40	0.47
Fe_2O_3	0.61	-0.59	0.23	0.29	-0.83	0.05
FeO	0.89	0.23	-0.23	0.91	-0.09	0.23
MnO	0.82	0.09	-0.09	0.76	-0.23	0.24
MgO	0.93	0.02	-0.29	0.94	-0.25	0.08
CaO	0.84	0.22	-0.23	0.87	-0.07	0.21
Na_2O	0.40	0.50	0.71	0.09	-0.05	0.95
K_2O	-0.56	-0.50	-0.48	-0.33	0.02	-0.82
P_2O_5	0.95	-0.03	-0.19	0.90	-0.34	0.14
U	-0.58	0.66	-0.22	-0.26	0.87	0.01
Th	-0.48	0.64	-0.41	-0.09	0.89	-0.11
Variance Explained By Factor	7.62	1.90	1.39	5.93	2.80	2.17
Percent Explained	69.84	17.42	12.74	54.40	25.69	19.91

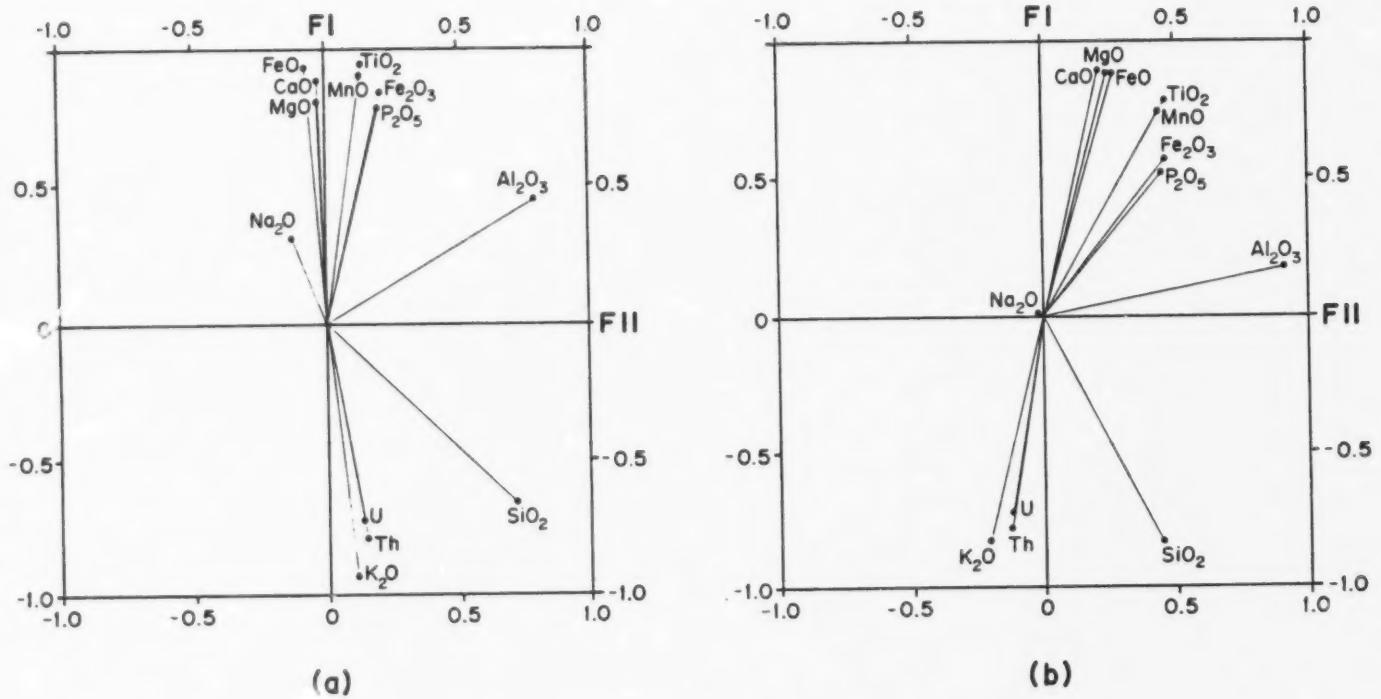


Figure 37. Plots of loadings on the first two factors extracted from U, Th and major element contents of the Charlotte Pluton; (a) original loadings, (b) after VARIMAX rotation.

TABLE 9.

Left Side: Square Multiple Correlation (SMC) and Communalities of the Variables; Right Side: Eigenvalues and Percent of Variances Accounted for each of the Factors for U, Th, Minor and Trace Element Contents in the Charlotte Pluton.

Elements	SMC	Communalities (h^2)
Sr	0.96	0.77
Rb	0.95	0.85
Zr	0.97	0.73
F	0.75	0.96
Ni	0.94	0.82
Cr	0.97	0.80
Zn	0.95	0.72
Cu	0.94	0.93
U	0.96	0.74
Th	0.97	0.75

Factors	Eigenvalues	Percent Variance	Cumulative Percent
I	5.22	52.20	52.20
II	1.66	16.60	68.80
III	1.20	12.00	80.80
IV	0.80	8.00	88.80
V	0.65	6.50	95.30
VI	0.25	2.50	97.80
VII	0.14	1.40	99.20
VIII	0.05	0.50	99.70
IX	0.02	0.20	99.90
X	0.01	0.10	100.00

Table 10.
Original and VARIMAX-rotated Factor Loadings
for the First Three Factors Retained for U, Th, Minor and
Trace Elements of the Charlotte Pluton.

Factors / Variables	Unrotated Factor Loadings			Rotated Factor Loadings		
	F I	F II	F III	F I	F II	F III
Sr	0.85	0.13	-0.17	0.83	0.10	-0.25
Rb	-0.88	0.10	0.27	-0.86	0.14	0.31
Zr	0.85	0.08	0.04	0.85	0.08	-0.03
F	-0.12	-0.16	0.96	-0.05	-0.03	0.98
Ni	0.80	-0.30	0.31	0.82	-0.26	0.29
Cr	0.58	0.66	0.14	0.59	0.67	0.01
Zn	0.83	0.11	0.12	0.84	0.12	0.04
Cu	-0.16	0.95	0.07	-0.15	0.95	-0.05
U	-0.76	0.39	0.12	-0.75	0.40	0.11
Th	-0.84	-0.11	-0.15	-0.85	-0.13	-0.07
Variance Explained By Factor	5.22	1.66	1.20	5.20	1.65	1.23
Percent Explained	64.60	20.54	14.86	64.36	20.42	15.22

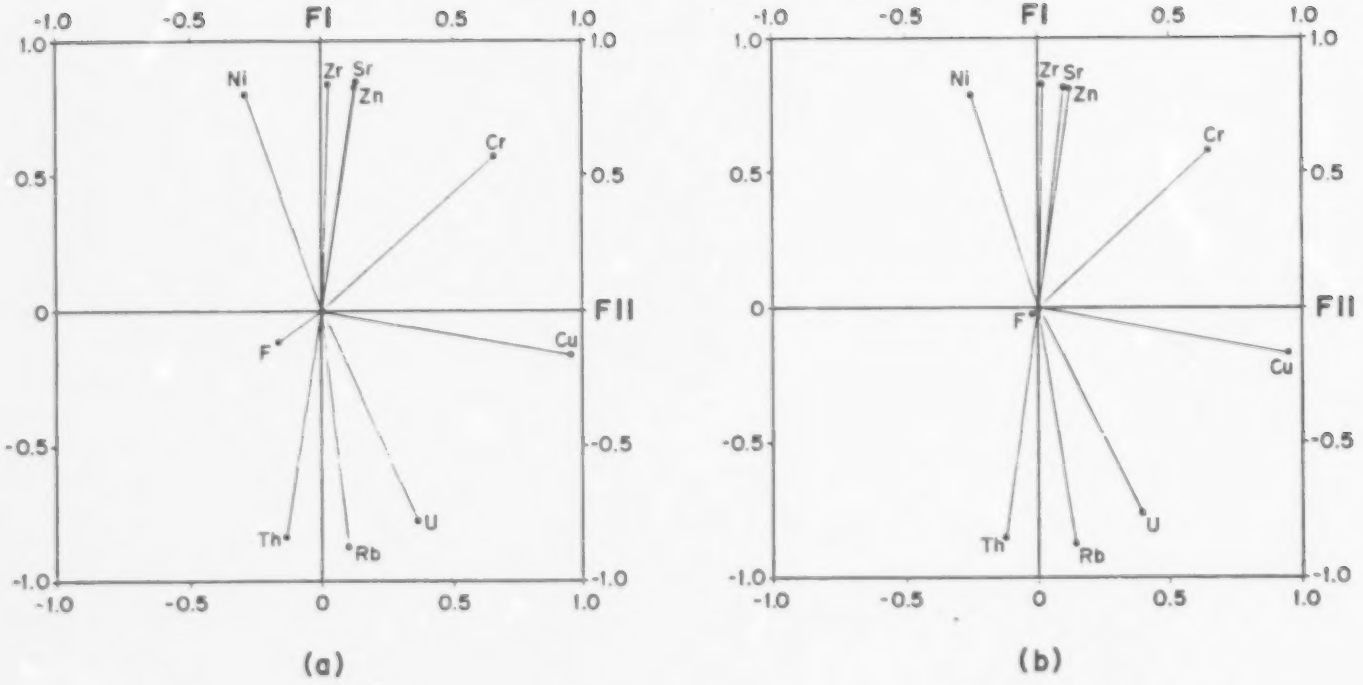


Figure 38. Plot of loadings on the first two factors extracted from U, Th and trace element contents of the Charlotte Pluton; (a) original loadings, (b) after VARIMAX rotation.

Table 11.
Mean and Standard Deviation of the Abundances of Major, Minor and Trace Elements of Granitic Stocks of Southwestern New Brunswick

ELEMENTS	BEECH HILL AND SOUREL RIDGE STOCKS		MILLTOWN STOCK		LAGLE LAKE STOCK		PLEASANT RIDGE STOCK		TOWER HILL STOCK		SOUTH OROMOCTO DIKE		MONASSAS STOCK		MISQUASH STOCK	
	PORPHYRITIC GRANITE		GRANITE		ADAMELLITE TO GRANITE		ADAMELLITE		ADAMELLITE		GRANITE		ADAMELLITE AND GRANODIORITE		PINK ADAMELLITE	
	n	Dev	n	Dev	n	Dev	n	Dev	n	Dev	n	Dev	n	Dev	n	Dev
SiO_2 ( )	17	75.95±3.16	7	67.89±6.89	9	71.97±2.42	2	75.17	2	74.09±1.61	2	74.35	2	71.29	4	73.85±1.13
TiO_2 ( )	17	0.21±0.09	7	0.28±0.22	9	0.29±0.13	2	0.12	3	0.23±0.06	2	0.26	2	0.35	4	0.22±0.05
Al_2O_3 ( )	17	12.25±1.15	7	15.51±2.48	9	13.40±1.18	2	14.01	3	14.62±.40	2	13.77	2	14.55	4	13.40±0.22
Fe_2O_3 ( )	17	0.84±0.41	7	1.02±0.59	9	0.85±0.23	2	0.32	3	0.58±0.17	2	0.32	2	0.83	4	1.07±0.19
FeO ( )	16	0.77±0.43	7	2.21±1.71	9	1.62±0.38	2	0.88	3	0.69±0.40	2	0.47	2	1.43	4	0.90±0.19
MnO ( )	17	0.02±0.02	7	0.06±0.04	9	0.04±0.03	2	0.07	3	0.18±0.21	2	0.04	2	0.05	4	0.02±0.02
MgO ( )	17	0.22±0.13	7	1.37±1.26	9	0.51±0.26	2	0.05	3	0.41±0.39	2	0.16	2	0.55	4	0.60±0.17
CaO ( )	17	0.67±0.69	7	3.16±2.42	9	1.14±0.53	2	0.19	3	0.55±0.32	2	0.25	2	0.57	4	2.12±0.73
Na_2O ( )	17	3.33±1.03	7	3.77±0.46	9	4.55±0.56	2	4.32	3	3.19±0.39	2	4.10	2	3.40	4	3.37±0.38
K_2O ( )	17	4.18±1.09	7	3.15±1.08	9	4.13±0.48	2	4.50	3	4.25±0.40	2	4.79	2	4.10	4	3.15±1.22
P_2O_5 ( )	17	0.04±0.02	7	0.15±0.16	9	0.07±0.02	2	0.01	3	0.10±0.01	2	0.07	2	0.17	4	0.07±0.01
Sr (ppm)	17	51.65±34.37	7	275.29±206.97	9	243.7±106.94	-	-----	3	97.67±51.64	2	29.00	2	137.50	4	104.25±61.35
Rb (ppm)	17	491.00±105.07	7	211.43±61.3	9	161.22±21.01	2	1462.00	3	204.67±122.7±	2	393.50	2	173.50	4	84.75±25.68
Zr (ppm)	17	122.88±59.44	7	120.29±44.85	9	134.00±47.97	2	8.00	3	79.33±36.83	2	50.00	2	106.50	4	121.25±9.46
Ni (ppm)	17	12.33±9.14	7	20.86±22.85	9	5.30±2.91	-	-----	3	3.67±4.62	2	2.00	2	6.00	4	1.33±14.57
Zn (ppm)	17	43.47±28.11	7	50.71±24.57	9	46.30±21.39	2	69.50	3	70.67±30.92	2	47.00	2	63.50	4	17.25±5.25
Cu (ppm)	17	10.70±3.18	7	15.86±7.72	9	11.33±3.00	2	5.00	3	9.33±5.13	2	9.00	2	6.00	4	12.00±0.82
Pb (ppm)	17	45.66±11.91	7	37.28±21.72	9	42.33±12.67	2	58.50	3	43.00±11.79	2	79.00	2	75.00	4	19.00±13.89
Co (ppm)	17	6.94±5.31	7	8.14±3.62	9	6.44±1.67	2	2.50	3	5.33±2.08	2	4.00	2	5.50	4	10.50±5.07
Li (ppm)	17	67.41±42.53	7	28.71±14.44	9	11.22±7.58	2	795.50	3	65.00±29.31	2	129.00	2	58.00	4	9.50±5.32
Be (ppm)	16	361.56±145.35	7	516.00±139.79	9	616.22±285.23	2	50.00	3	356.33±103.69	2	109.00	2	576.50	4	716.00±317.1
U (ppm)	17	11.82±8.18	7	2.17±0.96	9	3.76±3.96	2	14.50	3	3.70±1.04	2	21.56	2	2.45	4	5.02±7.37
Th (ppm)	17	41.70±15.07	7	5.71±5.53	9	21.73±7.17	2	30.00	3	15.67±5.69	2	20.50	2	11.00	4	11.50±3.32
Th/U	17	3.67±1.62	7	3.07±0.97	9	4.36±1.62	2	2.14	3	4.19±1.45	2	0.96	2	4.49	4	5.09±3.38

Butt (1976) concluded that the chemical composition of the pre-Acadian stocks was markedly changed by orogenic processes after their emplacement. Thus, it is impossible to trace their crystallization history. The post-Acadian magmas crystallized at different depths: some at relatively deeper levels (e.g., Tower Hill Stock, Pleasant Ridge Stock and South Oromocto Dyke) and others at more shallow levels (e.g. Beech Hill and Sorrel Ridge stocks). The chemical composition of the post-orogenic instrusions is different from the pre-orogenic intrusions in that they have higher SiO_2, K_2O and Na_2O and lower CaO, MgO and FeO contents (Butt, 1976).

Although the number of samples analyzed is small, the limited evidence available indicates that, for rocks of similar SiO_2 content, both U and Th are less abundant in the pre-orogenic stocks than the post-orogenic stocks (Figure 39). Furthermore, if the global average Th/U ratio of about 4.0 for granites is taken into consideration, then a preferential leaching of U relative to Th has taken place in the pre-Acadian intrusive rocks. The depletion of U in the pre-Acadian stocks is probably due to the release of U along shear zones generated by later orogenic activity in the area and/or by metamorphic processes associated with these orogenies. Alternatively, Th is proportionally more abundant than U in the pre-Acadian instrusive rocks.

In general, both U and Th contents in the post-Acadian instrusive rocks tend to increase with the increasing abundance of SiO_2 (Figure 39). The abnormally low U and Th contents of the Tower Hill stock, despite its high SiO_2 content, suggest that these rocks have crystallized from a magma derived from a source region of low U and Th content. This is supported by the average Th/U ratio of 4.18 for these rocks, which is close to the global average Th/U ratio for granites. Alternatively, both U and Th could have been depleted in these rocks by metamorphism.

Both U and Th are strongly enriched relative to the global average in the high-level, post-Acadian intrusive rocks of Beech Hill and Sorrel Ridge stocks. The Th/U ratio of the Beech Hill and Sorrel Ridge stocks is 3.97, which is close to the global average. This indicates that the rocks of Beech Hill and Sorrel Ridge stocks probably crystallized from magmas that initially contained high U and Th and that U has not been preferentially leached.

The preferential enrichment of U relative to Th in the South Oromocto Dyke, as well as the Pleasant Ridge Stock and two samples from the Beech Hill and Sorrel Ridge stocks is indicated by Figure 40; these samples are well separated from the other samples on the diagram. The granitic stocks follow a roughly linear trend with the most mafic stock (Milltown) containing

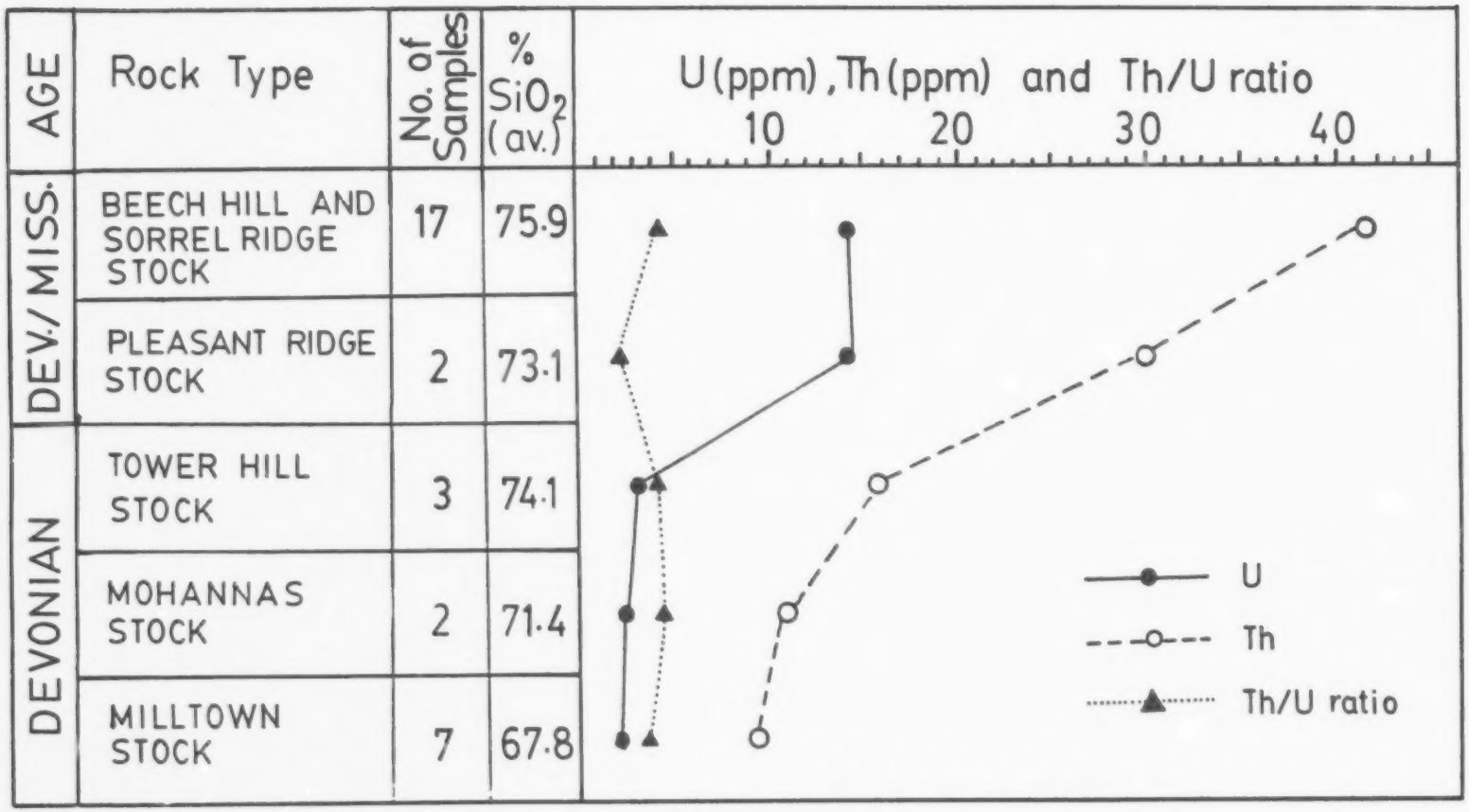


Figure 39. Variation of the mean U, Th, Th/U ratio and SiO_2 content of the granitic stocks.

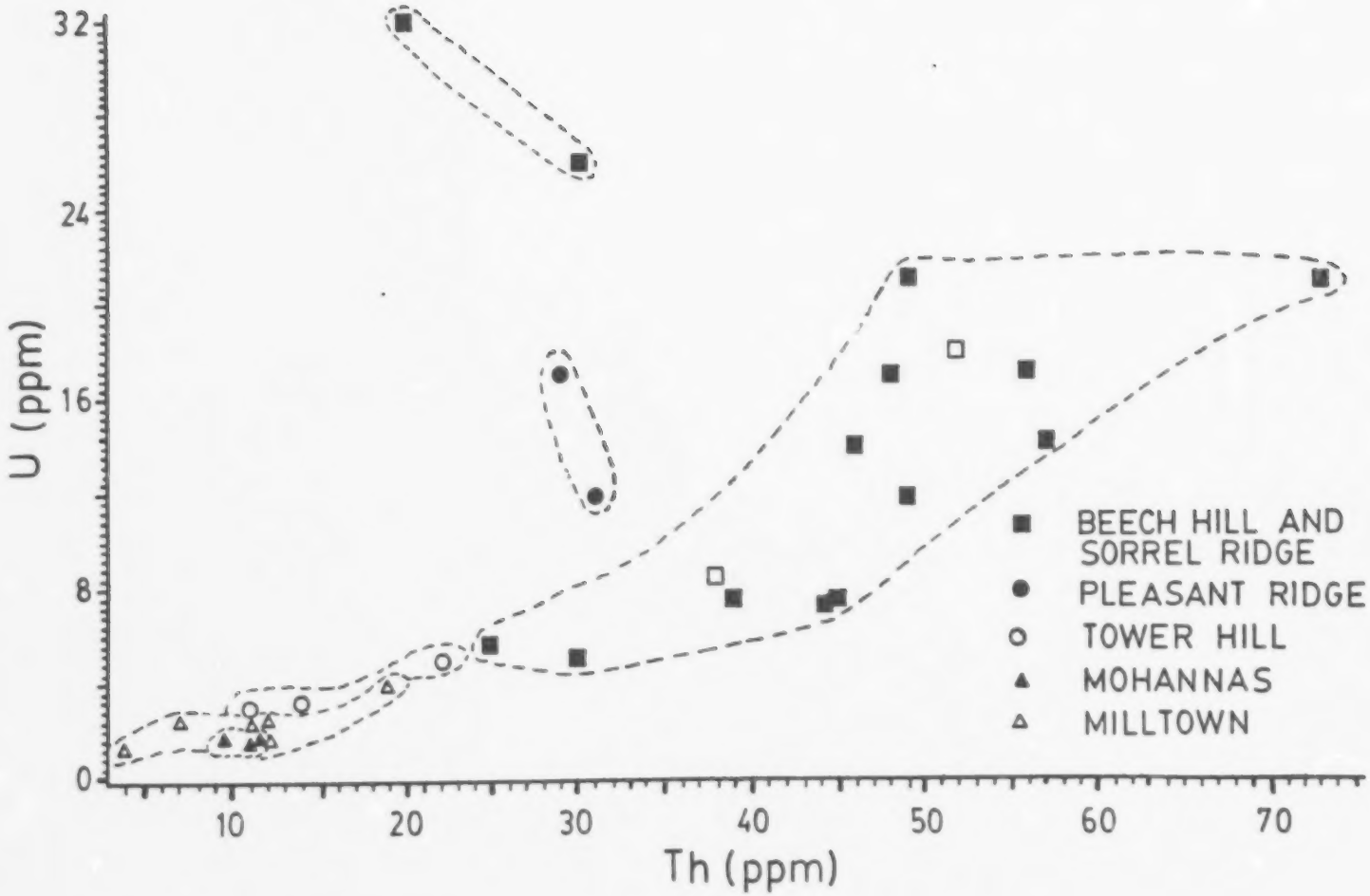


Figure 40. U-Th relations in the granitic stocks.

the least U and Th, whereas the highest U and Th contents are confined to the youngest and more felsic stocks (Beech Hill and Sorrel Ridge).

The major- , minor- and trace-element data (Table 11) characterize the Beech Hill and Sorrel Ridge stocks as 'uraniferous'and 'thoriferous' according to Darnley's (1982) definitions. Compared to the global average composition of granites (Table 4), these stocks exhibit higher contents of SiO_2, Na_2O, Rb, Ni, Pb and Co and lower contents of Al_2O_3, FeO, MgO, CaO, P_2O_5, Sr and Ba.

VOLCANIC ROCKS OF THE MOUNT PLEASANT AREA

Table 12 indicates the expected increase in both U and Th as the volcanic rocks become more felsic. Uranium ranges from 0.9 ppm in the basalt to about 5.0 ppm in the fresh rhyolite, whereas Th ranges from 4.0 ppm to about 25.0 ppm in the same rock units. The intercorrelation matrix for these rocks (Figure 41) reveals that U is positively correlated with SiO_2, K_2O and Rb but negatively correlated with Al_2O_3, FeO, MnO, MgO, CaO, P_2O_5 and Sr. Thorium behaves similarly. In general, a good positive correlation exists among U, Th, SiO_2 and Rb. K_2O correlates moderately with U, but it has poor correlation with Th (Figure 42). Zn and Sn have a poor negative correlation with both U and Th.

CONCLUSIONS

eU and eTh DETERMINATIONS FOR ROCKS OF SOUTHWESTERN NEW BRUNSWICK

The following conclusions were reached from the results of eU and eTh determinations in the study area:

1. Within the Devonian intrusive and volcanic rocks, variation in U and Th probably corresponds with the differentiation history of these rocks. During the process of magmatic evolution, both U and Th contents tended to increase from the early mafic rocks to the late felsic varieties. The increase in both U and Th content is gradual in the volcanic rocks, but both U and Th contents increase rapidly in the final stages of crystallization of the intrusive rocks. This is to be expected because U and Th are both trace elements incompatible with the major rock-forming minerals.

2. The post-Acadian rocks (excluding Pennsylvanian) have higher U and Th contents than the pre-Acadian rocks. Furthermore, the Devonian granitic rocks of the Charlotte Pluton and the Mississippian rhyolitic rocks at Harvey Station have higher U and Th potential than the other rocks.

Table 12.
Mean and Standard Deviation of the Abundances of Major, Minor and Trace-element Contents in the Mississippian Volcanic Rocks of the Mt. Pleasant area

ELEMENTS	RHYOLITE n	RHYOLITE mean	ALTERED RHYOLITE n	ALTERED RHYOLITE mean	RHYODACITE n	RHYODACITE	ANDESITE n	ANDESITE	BASALT n	BASALT
SiO_2 (%)	8	73.60±1.39*	4	76.50±3.36	1	67.66	1	55.54	1	46.54
TiO_2 (%)	8	0.28±0.09	4	0.18±0.08	1	0.67	1	1.45	1	3.82
Al_2O_3 (%)	8	13.55±0.80	4	12.44±1.46	1	13.93	1	16.30	1	15.91
Fe_2O_3 (%)	8	1.45±0.78	4	1.26±0.23	1	1.43	1	1.75	1	6.45
FeO (%)	8	0.73±0.33	4	0.86±0.39	1	3.24	1	4.08	1	6.71
MnO (%)	8	0.05±0.03	4	0.01±0.01	1	0.10	1	0.14	1	0.31
MgO (%)	8	0.54±0.16	4	0.48±0.23	1	0.93	1	6.96	1	4.61
CaO (%)	8	0.50±0.37	4	0.23±0.04	1	1.88	1	4.33	1	4.41
Na_2O (%)	8	1.98±0.91	4	1.10±1.30	1	3.27	1	3.95	1	4.35
K_2O (%)	8	6.03±0.53	4	5.60±1.35	1	5.11	1	2.89	1	1.41
P_2O_5 (%)	8	0.18±0.10	4	0.11±0.03	1	0.35	1	0.88	1	1.09
H_2O (%)	8	0.37±0.15	4	0.46±0.36	1	0.13	1	0.65	1	1.05
Cu (ppm)	8	7.37±4.10	3	8.67±7.23	1	8.00	1	23.00	1	5.00
Pb (ppm)	8	44.00±16.96	3	41.67±10.26	1	37.00	1	47.00	1	23.00
Zn (ppm)	8	78.12±22.96	3	68.67±26.31	1	85.00	1	115.00	1	148.00
Sn (ppm)	8	6.75±3.81	3	6.00±3.46	1	10.00	1	10.00	1	18.00
Sb (ppm)	8	6.75±3.88	3	14.00±9.64	1	7.00	1	3.00	1	28.00
Rb (ppm)	8	266.25±43.20	3	227.33±12.06	1	130.00	1	69.70	1	37.09
Sr (ppm)	8	119.54±95.11	3	59.33±51.62	1	175.00	1	743.90	1	153.50
U (ppm)	8	4.99±1.17	4	5.25±1.44	1	3.10	1	1.90	1	0.90
Th (ppm)	8	25.62±8.88	4	28.50±10.08	1	14.00	1	7.00	1	4.00
Th/U	8	2.25±1.12	4	5.39±1.14	1	4.52	1	3.68	1	4.44

n = number of samples

* error above the mean expressed by the standard deviation.

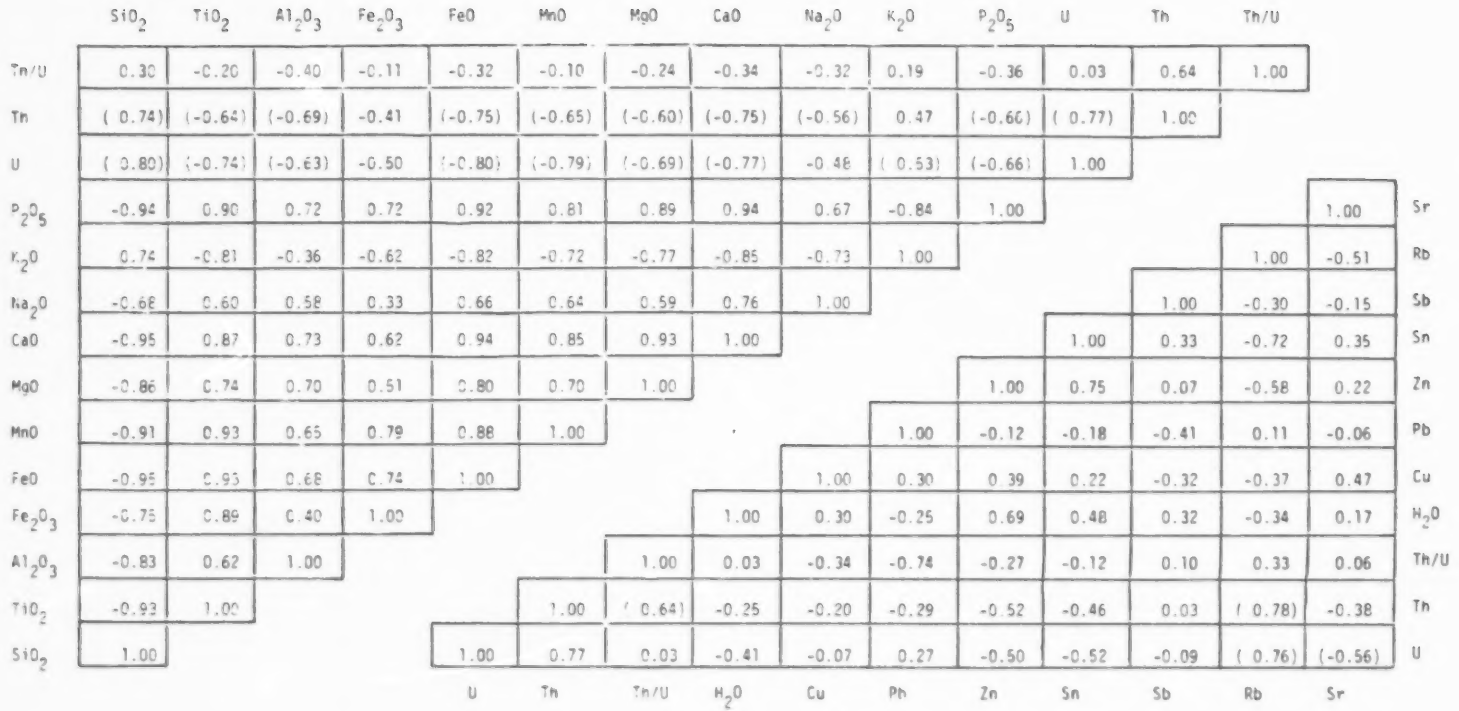


Figure 41. Correlation matrix for 15 samples of Mississippian volcanic rocks. Values in brackets indicate significant correlations with U and Th at the 95% confidence level.

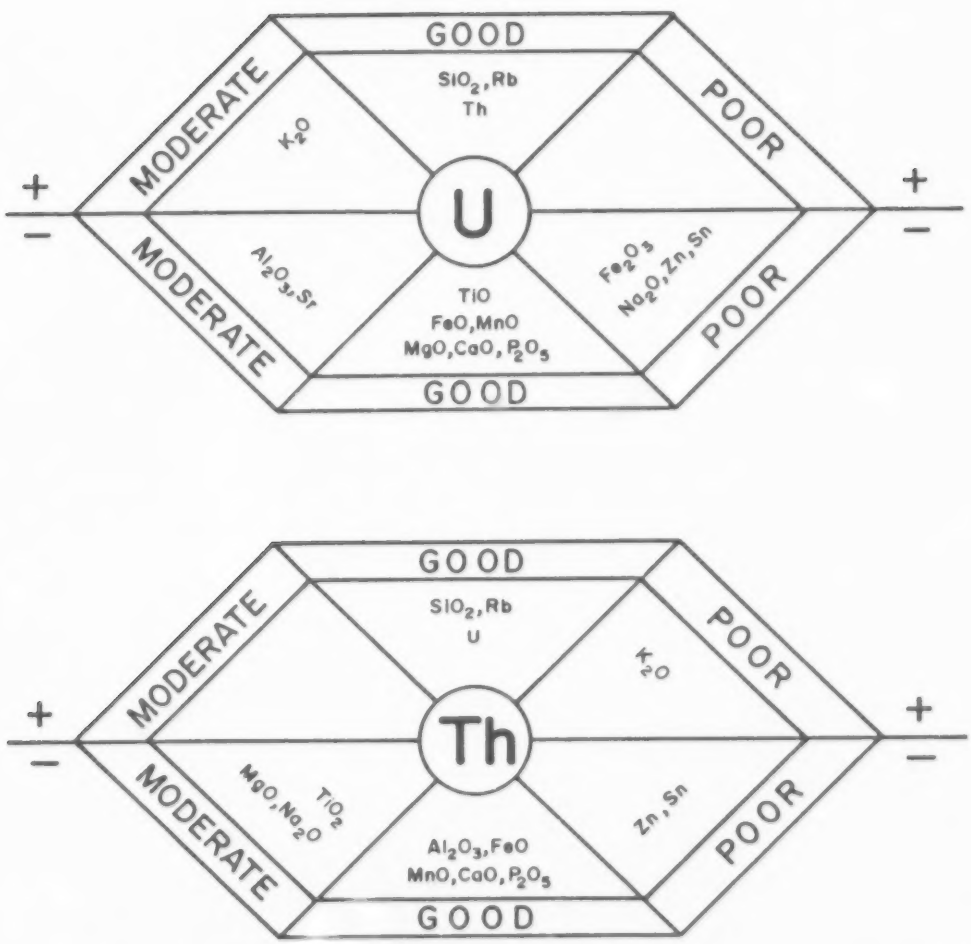


Figure 42. Summary diagram of the degree of correlation between major, minor, and trace elements, and U and Th in Mississippian volcanic rocks of the Mount Pleasant area.

3. The mean eTh/eU ratio appears to increase with the degree of magmatic differentiation in the Devonian Eastport volcanic rocks. However, this ratio varies erratically with magmatic differentiation indices in the Devonian St. George Batholith rocks. The variation is attributed to the complex history of U leaching and redistribution within the plutonic rocks.

4. The mean eTh/eU ratio for most of the granitic rocks in the study area is greater than the typical Th/U ratios of between 3.5 to 4.0 in global average granites (Rogers and Adams, 1978). This may be attributed to higher Th enrichment relative to U and the time of the granitic rocks' emplacement, or to post-crystallization loss of U by weathering, metamorphism and alteration processes. The latter explanation is favoured since field data was obtained mainly from surface rocks and truly fresh samples are extremely difficult to obtain. Furthermore, Th in the igneous rocks appears to be correlated with K content, whereas U shows little correlation with K, suggesting a high mobility of U relative to Th and K in the post-crystallization processes.

5. Uranium and thorium abundance increases with decreasing age of the rocks in the study area. The low eU and eTh contents of the post-Acadian Chance Harbour granite (Pennsylvanian), relative to other granitic rocks in the study area, is an exception to this trend. The Chance Habour granite may have been derived from a source material containing lower amounts of U and Th than the sources for the other granite. Alternatively, U and Th in the Chance Harbour granite may have been remobilized and removed.

6. The trend of increasing U and Th content with decreasing age could be related to one or more of the following factors: (a) Weathering processes play a significant role in U leaching. Although readings were taken on fresh surfaces as much as possible to minimize the effects of weathering, it was not always possible to select a truly fresh rock for gamma-ray spectrometric assaying. (b) Southwestern New Brunswick was subjected to at least two major phases of deformation: the Taconian and the Acadian orogenies. The intensity of deformation in the rocks of the study area is, therefore, much greater in the older rocks. These deformations produced fracture zones that served as channelways for percolating water. Therefore, a considerable amount of U could have been leached from the older rocks. (c) The older rocks are more highly metamorphosed than the younger rocks. It is well known that both U and Th can be released from rocks by metamorphism. Therefore, it is likely that both U and Th have been depleted from the rocks by metamorphism. (d) Progressive reconcentration of earlier depleted U and Th by the above processes in younger rocks is also possible. The U and Th contents of the post-Acadian rocks of southwestern New Brunswick, which are not affected by major deformation or metamorphism, are higher than those in the pre-Acadian rocks.

(e) The older igneous rocks in the study area are probably derived from an original source magma poor in U and Th, whereas the younger igneous rocks may have been derived from a source richer in U and Th. (f) The older igneous rocks in the study area are apparently less differentiated than the younger igneous rocks and hence the older igneous rocks contain less U and Th than the younger igneous rocks.

U AND TH DETERMINATIONS FOR THE ST. GEORGE BATHOLITH

The results of U and Th determinations for the rocks of the St.George Batholith suggest that:

1. The U and Th distribution in the rocks of the St. George Batholith (Figure 43) is typical of calc-alkalic suites of igneous rocks in that both U and Th display a curvilinear increase in the SiO_2 content. Both U and Th increase in abundance approximately nine-fold from the mafic to the felsic comagmatic rocks.

2. Of the various geochemical indices investigated with respect to U and Th distribution in rocks of the St. George Batholith, the felsic index (100 (Na+K)/Na+K+Ca) is apparently the best indicator of U increase with degree of magmatic differentiation, while the Harker index (SiO_2 content) is better for Th, especially for the rocks of the Charlotte Pluton.

3. Both U and Th are poorly correlated with degree of alumina saturation (molecular proportion $(Al_2O_3/CaO+Na_2O)$) for rocks of similar composition. However, the peraluminous rocks of the Charlotte Pluton are, in general, higher in U and Th contents than the metaluminous rocks of Bocabec Intrusive Complex.

4. Both U and Th are apparently slightly affected by the oxidation state (Fe_2O_3/FeO) that prevailed in the rocks of the St. George Batholith during its crystallization.

5. The Th/U ratio in rocks of the St. George Batholith ranges from 1.8 to 9.0. The range is narrow for the rocks of the Bocabec Intrusive Complex, but wide for the rocks of the Charlotte Pluton, particularly in its eastern end. This wide range in Th/U ratio appears to be related to late magmatic processes and weathering. Furthermore, it appears that the Th/U ratio has followed three distinct trends during the late stage of crystallization of the St. George Batholith: a) uranium is preferentially depleted relative to Th in the porphyritic granite, and b) and c) enriched relative to Th in the coarse-grained granite and aplite of the Charlotte Pluton.

6. The values of statistical correlation coefficients between U and Th and the major elements show that both U and Th have a strong positive correlation with SiO_2 and K_2O for the rocks of the St. George Batholith when treated as a single unit. But if only rocks of the Charlotte Pluton are considered, both U and Th have a poor positive correlation with SiO_2 possibly

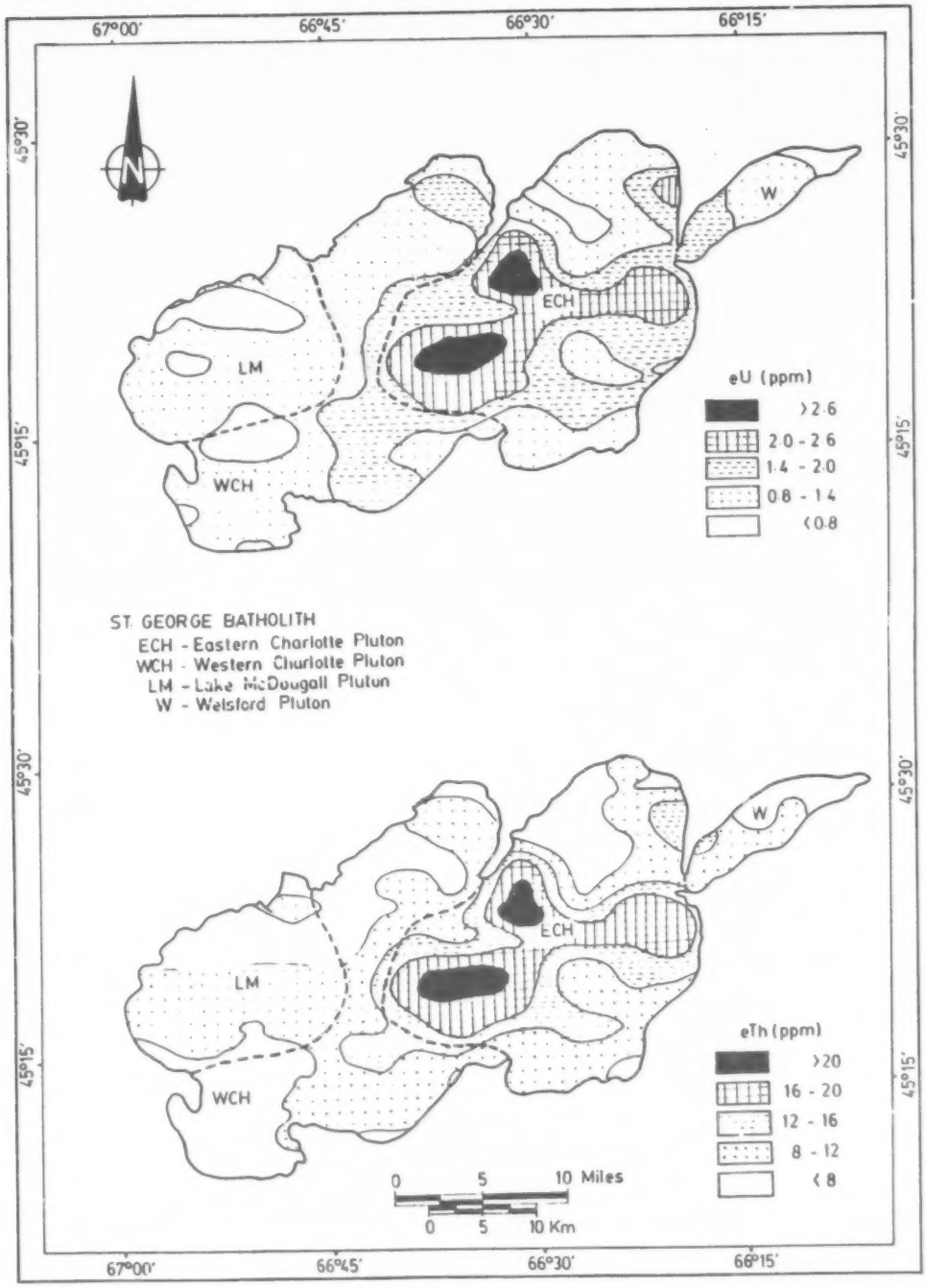


Figure 43. Contours for equivalent uranium and equivalent thorium over the St. George Batholith.

because of U and Th redistribution by post-magmatic processes in these rocks. With respect to the trace elements in the Charlotte Pluton, both U and Th show strong positive correlations with Rb.

7. No statistically significant correlation of U and Th with F exists in the rocks of Charlotte Pluton. This is suggested to be caused by the formation of neutral to alkaline hydrothermal solutions at the last stages of magmatic differentiation; under such conditions small amounts of U and Th form complexes with F.

8. There is a spatial variation in U and Th distribution between the eastern and western ends of the Charlotte Pluton. Their abundances in the eastern end are greater than in the western end. These variations extend below surface in the rocks and are consistent with the chemical, mineralogical and textural data (Cherry, 1976).

9. It is suggested that the Charlotte Pluton is a 'uraniferous' granite because it contains U in twice the amount of 'average' granite and also it has a strong similarity to uraniferous granitoids of the British Caledonides in its whole rock chemistry, mineralogy, tectonic setting and geophysical aspects. Similarly, the term 'thoriferous' is adopted in this study to designate the Charlotte Pluton, since it contains twice as much Th as the 'average' granite. Compared to 'average' granites, the Charlotte Pluton exhibits higher contents of SiO_2, Na_2O, K_2O, Rb and Ni and lower contents of Al_2O_3, FeO , MgO, CaO, P_2O_5, Sr and Cu. The low level of F in the Charlotte Pluton relative to other uraniferous granite was unanticipated and can be explained by the loss of F in an aqueous volatile phase.

10. The overall U and Th distribution in surface and near-surface rocks of the St. George Batholith suggests that J and Th are mainly controlled by magmatic differentiation and perhaps later modified by hydrothermal and supergene processes according to the proposed model shown in Figure 44. According to this model, partial melting of relatively U- and Th-rich sialic crust generated felsic magma which, upon crystallization and differentiation, gave rise to the rocks of the St. George Batholith. Because of the limited substitution of U and Th for cations of the major rock-forming minerals, they became progressively more concentrated in the melt than in coexisting crystals during magmatic differentiation. Liquidus crystallization of major rock-forming minerals also causes a progressive enrichment of dissolved volatiles and other large lithophile elements such as Rb and K in the residual melt. At the apex of magmatic differentiation, and when at least 90% (Cherry, 1976) of total magma had been crystallized (near the eastern end of the batholith), the magma became water-saturated and enriched in other dissolved volatiles (particularly F). At this stage the pressure of the volatiles exceeded the external pressure and the volatiles escaped out of solution to form a separate water-rich

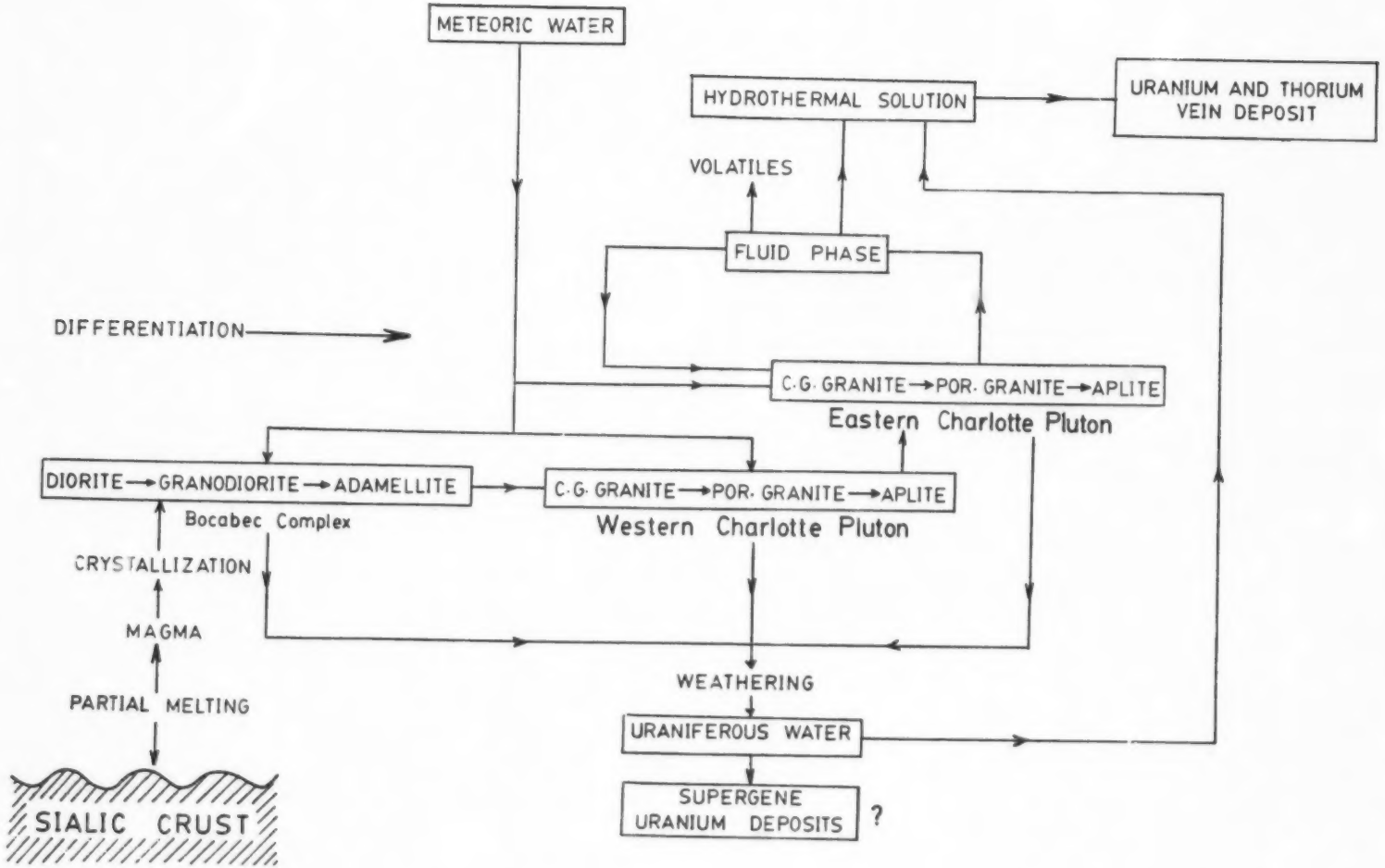


Figure 44. A proposed model for the U and Th distribution in the rocks of the St. George Batholith.

phase or hydrothermal solution. Uranium preferentially was fractionated into the hydrothermal solutions where it occurred as uranous or uranyl fluoride complexes. Langmuir (1978a) indicates that such complexes are readily soluble under acid conditions. These hydrothermal solutions then percolated along fractures and formed the U and Th mineralized zone discovered at the eastern end of the Charlotte Pluton. The alteration (silicification and hematization) of the wall rocks supports the contention that hydrothermal processes were operative. The uranite and thorite minerals formed in this zone, and the spatial association between this zone and the Charlotte Pluton, suggest that the source of the uranium and thorium is more likely the pluton than other country rocks. The high U and Th contents and high Th/U ratio in surficial rocks of the Charlotte Pluton and the high U content in deeper samples (diamond drill core) also support the hypothesis that the source of U and Th vein mineralization is the Charlotte Pluton.

According to Langmuir (1978b), the precipitation of fluoride ion as fluorite reduces uranous ion mobility in solutions and leads to the precipitation of uraninite and thorite. But it appears that is not the case with uranium mineralization in the coarse-grained granite of the eastern Charlotte Pluton as fluorite does not accompany the U mineralization. It is possible that the calcium concentration was not sufficiently high in these hydrothermal solutions to allow the precipitation of fluorite in the vicinity of the U mineralization. The lack of association U and Th with F is also demonstrated by the poor statistical correlation of both U and Th with F in the rocks of Charlotte Pluton. Alternatively, it is also possible that U and Th precipitated from neutral or alkaline hydrothermal solutions (formed by interaction of presumably acid hydrothermal solutions with alkaline groundwater); and under such conditions there is little U and Th complexing with F.

The depletion of U from the surface and near-surface rocks of the western end of the Charlotte Pluton is believed to be the result of weathering because Th has not been depleted at similar depths in the same environment. Uranium is readily removed by weathering, but Th is not. This conclusion is supported by the presence of several U anomalies in stream water and sediments located in the vicinity of the western end of the St. George Batholith. The uraniferous water formed at the zone of weathering might be added to the hydrothermal system in the pluton or transported through fractures until it interacts with reducing environments and forms supergene U deposits.

U AND TH DETERMINATIONS FOR GRANITIC STOCKS

The results of U and Th determinations for the rocks of the granitic stocks in southwestern New Brunswick indicate that:

1. For rocks of similar SiO_2 content, both U and Th are enriched in the post-Acadian intrusions relative to the ear-

lier ones. This is attributable to successive depletion of U and Th by orogenic activity and/or by metamorphic processes associated with these orogenies, or, alternatively, to the lower U and Th contents of the source magma of the pre-Acadian stocks.

2. In the post-Acadian granitic stocks, both U and Th abundances are related to the composition of the source magmas and to the level of their emplacement in the crust. Low contents of U and Th are found in those stocks that crystallized at deeper levels, while higher contents of U and Th are found in those stocks emplaced at more shallow levels. Those stocks that have higher U and Th contents than the global average for granites are similar in their whole-rock chemistry to the uraniferous granites of the Charlotte Pluton and the British Caledonides.

U AND TH DETERMINATIONS FOR MISSISSIPPIAN VOLCANIC ROCKS OF THE MOUNT PLEASANT AREA

The results of U and Th determinations of the Mississippian volcanic rocks of the Mount Pleasant area suggest that:

1. Both U and Th increase in abundance with the degree of magamtic differentiation by a factor of about five for U and six for Th.

2. Both U and Th have a strong positive correlation with the abundance of SiO_2 and Rb.

3. In contrast to the unaltered rhyolitic rocks of the same suite, both U and Th increase with the degree of silicification of the rhyolitic rocks.

GUIDELINES FOR URANIUM AND THORIUM EXPLORATION IN SOUTHWESTERN NEW BRUNSWICK

1. Most of the U occurrences investigated in the study are spatially and probably genetically associated with the post-Acadian volcanic and plutonic felsic rocks that display higher U and Th contents than average granitic rocks. The Mississippian volcanic rocks of the Harvey Station area contain known uranium prospects. Uranium vein mineralization was found, during this study, in the coarse-grained granite of the Charlotte Pluton. The uranium mineralization in the Harvey area, particularly at York Mills and Manners Sutton, lies in the vicinity of the Fredericton Fault that passes through these rocks and trends northeast-southwest. This fault could have served as a channelway for uranium-rich solutions passing through the Mississippian volcanic rocks of the Harvey area. The source of U is probably the volcanic rocks themselves since they contain more U than average volcanic rocks.

2. The radioelement mineralization in the Silurian/Devonian rhyolite, Devonian granite and Mississippian volcanic rocks is of some economic interest and these rocks represent valid targets for exploration. Whether these zones are, or will be, of any economic value is difficult to determine at this stage because of the limited number of samples and poor exposure of most of the mineralized zones. Furthermore, most of the information obtained is from the rock surface and there is an indication that part of the near-surface uranium mineralization might be leached away, presumably by weathering. Therefore, detailed sampling of the mineralized zones is recommended and holes should be drilled, particularly for the mineralized uranium and thorium zone discovered in this study at the eastern end of the Charlotte Pluton (Eagle Rock, Welsford), to determine the extent of these mineralized zones and the concentrations of U and Th at depth.

3. The relatively high U content of the Mississippian felsic volcanic rocks at Harvey Station and the Devonian granitic rocks of Charlotte Pluton indicates that these rocks are significant sources from which secondary uranium mineralization within the adjacent rocks is derived. Shear zones, unconformity surfaces and chemical alteration zones are among the best targets for secondary uranium mineralization. Therefore, detailed investigation in the vicinity of these zones should be carried out (e.g., soil and stream sediment sampling, and water sampling). Samples should be analysed for their U contents in order to determine the fate of the U leached from these sources. Shear zones extending from these rocks into the adjacent rocks should be investigated carefully for uranium vein mineralization.

4. Any future exploration for radioactive elements in southwestern New Brunswick should follow these guidelines:

a. Concentrate investigation on highly differentiated igneous rocks, particularly those of post-Acadian age.

b. Explore the eastern end of the St. George Batholith and the Mississippian rhyolitic rocks of Harvey Station.

c. Concentrate investigation on rocks exhibiting alterations, particularly those associated with unconformity surfaces and shear zones.

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